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Paul Waring

Main Building -
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ACOUSTICS

IN RELATION TO

ARCHITECTURE AND BUILDING

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ACOUSTICS

IN RELATION TO

ARCHITECTURE AND BUILDING:

THE LAWS OF SOUND

AS APPLIED TO

THE ARRANGEMENT OF BUILDINGS

BY

homas
T. ROGER SMITH, Architect

MEMBER OF THE ROYAL INSTITUTE OF BRITISH ARCHITECTS

New Edition

WITH TWENTY ILLUSTRATIONS ON WOOD, AND A GENERAL INDEX

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PREFACE.

This manual does not profess to furnish the reader with either facts or principles previously unknown. It has simply been framed with a wish to afford, in a somewhat connected form, as much information relative to the laws of sound and their application to the arrangement of buildings as could be collected from trustworthy sources.

Even to accomplish this much, however, it was necessary to institute a wide search; for this, the most practical application of the science of Acoustics, is a subject confessedly obscure, and has been but little studied. The very names of the few authors who have written upon it were not extensively known, and much that seemed to bear upon the subject had to be procured rather from the personal testimony of those practically acquainted with buildings, than from books. It became, therefore, necessary to trespass largely on the kindness of professional and scientific men; and the Author has much pleasure in acknowledging the assistance he has received from many sources.

Thanks are especially due to Mr. Walters and Mr. Horace Jones, for the use of the drawings from which the illustrations of the Free Trade Hall and the Surrey Music Hall have been prepared; and to Professor Faraday, for the opportunity of giving an illustration of the Lecture Theatre of the Royal Institution; also to Professor Wheatstone, Mr. Scott Russell, Mr. P. C. Hardwick, Mr. Pennethorne, Mr. Hullah, Mr. Holland, and other gentlemen, for valuable information and assistance.

Although it is believed that this work, small as it is, will be found more comprehensive than any previously existing in English, yet no one can be more aware than the author of the incompleteness of what has been done. Should any of his readers find themselves able either to correct errors into which he may have fallen, to furnish information tending to elucidate any of the many points which he has been unable to clear up, or to corroborate any of his views, they will confer a kindness by communicating with him.

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THE ACOUSTICS
OF
PUBLIC BUILDINGS.

SECTION I.

THE SCIENCE OF ACOUSTICS.

Acoustics * may be defined as the science of sound and hearing, and a general statement of the leading principles recognised as forming the basis of that science will appropriately introduce that special application of them which forms the subject of the present volume.

Although the works which treat of the adaptation of acoustics to buildings are but few and little known, the science of acoustics itself has been extensively if not completely investigated, and is treated of in many works, some elementary and others deeply abstruse. On this, as well as other accounts, anything like a complete treatise would be quite out of place here, and it is consequently not proposed to attempt more than a popular and very general outline of what modern science has established with regard to sound, adding here and there an illustration of those elementary principles upon which any correct theories affecting the construction of buildings must of necessity be based.

It is unfortunate that so few of the philosophers who have

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* From the Greek word, ἀκουστικὸν, "relating to hearing." This derivation indicates the correct pronunciation of the second syllable, which should be sounded as the word *cow*, and not as the word *coo*, although the latter sound is correct where the continental pronunciation of Greek is followed, as is the case in Scotland.

devoted their time to this study have paid any attention to the most practical of all its possible applications, and that consequently an idea has become prevalent that nothing at all is known to men of science which would be of value to the architect. It has become but too customary to apply to any set of requirements or circumstances, any expedient, or material, or contrivance, which has ever been believed to be advantageous in some previous instance, possibly a dissimilar one, and to give as a reason the general conviction that it is "good for sound," without any well defined idea what the result may be expected to be. This is to be deplored, as the principal laws of sound are well known, and an acquaintance with them, coupled with the requisite skill in the application of them will render success not only possible, but within ordinary limits certain.

One word, however, must be said upon the degree of dependence to be placed upon theoretical knowledge. Let it be ever borne in mind that in all branches of architectural practice, but in none so much as in that branch now under consideration, rules and principles never did, never will, and never can supersede the necessity for intelligence, judgment, tact, experience, and something of intuitive perception in their application. Practical architectural acoustics will always be in a position very much analogous to the practice of medicine. The physician, after he has gained all the knowledge of disease and of medicines which books can afford, is still quite unfit for actual practice unless he have the skill and intelligence to know how to vary his mode of treatment, and to suit his application of laws and principles to the different circumstances of each case, and the different constitution of each patient; and he must, moreover, possess a large stock of isolated facts relative to cases which do not seem reducible to our known general laws, nay, which even run counter to them. It is so with sound. The most successful architects will tell you that their judgment of the probable acoustic effect of this or that arrangement is as much, or more, the result of a sort of instinct—a kind of internal perception of what will do, or what will not do, as it is of the application of a code of laws, or a set of rules; and knowledge, to be of much value in this department, must be associated with a sort of tact, not to say instinct, which is not to be gained at once or easily, nor without making the subject one of constant observation and thought when visiting existing buildings, or when preparing or examining designs for new ones.

The following seven propositions comprise a general view of this subject. The first three relate to the nature of sound and sounding bodies, the following three to the propagation of sound, and the last one to its reinforcement.

I. Sound always originates in some movement of the body from which it is emitted, and becomes audible only when any conductor exists that will convey the motion of the sounding body to the ear.

II. Sounds differ in the properties of quality or tone, loudness, intensity, volume, pitch, and distinctness; they also vary in their nature, according as they take the form of noise, music, or articulate speech.

III. When rapid successive impressions on the ear follow at regular intervals, a continuous sound is heard (the pitch of which depends upon the frequency of the repetitions). Such notes are, in all but the most exceptional cases, caused by the vibrations of some elastic body.

IV. Sound is conveyed most frequently through the atmosphere, but nearly all bodies will transmit it.

V. Sounds traverse the air at an uniform rate of speed, but with a constantly diminishing strength; they naturally follow a straight course, but their direction is liable to be modified by the objects they meet—they are subject to be reflected, deflected, conducted, or absorbed.

VI. There is a great similarity between the laws that govern the propagation of sound and of light, but sometimes the propagation of sound in the atmosphere bears an analogy to that of undulations on the surface of water.

VII. Bodies capable of vibrating so as to produce any sustained sound, are ordinarily apt to vibrate spontaneously, when a sound of the same pitch is excited near them.

Sound and Sounding Bodies.

(1) "Sound always originates in some movement of the body from which it is emitted, and becomes audible only when any conductor exists that will convey the motion of the sounding body to the ear."

Sound appears to accompany nearly all motion, and probably movements too slow or too smooth to be audible to our ears might be appreciable to a more delicately organised hearing apparatus.

The actual force that attends very loud or very sudden sounds is familiarly known; the breaking of windows, and shaking of glasses, &c., by a discharge of artillery, an explosion, or even a loud thunder clap, are instances that show the actual impulse of very loud sounds to be considerable: such an impulse, though infinitely less in degree, attends even the faintest whisper.

The sense of hearing is really a refined and delicate sense of touch, and the impressions made upon the ear are due to actual motion made sensible through a conductor; and if any movement which would naturally be attended with sound takes place under circumstances that cut it off from all direct communication with the ear, no sound will be heard.

The best method of demonstrating this is to suspend a bell by a silken thread in the receiver of an air-pump, with a piece of clockwork for striking it; as long as air remains in the receiver the sounds of the bell are heard, but they grow fainter as the air is withdrawn, and when as complete a vacuum as mechanical means can obtain is created, no sound is heard at all.

(2) "Sounds differ in the properties of quality or tone, loudness, intensity, volume, pitch, and distinctness; they

also vary in their nature, according as they take the form of noise, music, or articulate speech."

The tone peculiar to any sound (employing the word tone, a word to which several meanings are assigned, to express the *nature* of the sound, as for example, a silvery, a brassy, a shrill, or a dull tone), though affected sometimes by other circumstances, such as the nature of the transmitting medium, or of the existing cause, is principally due to the nature of the substance by which the sound is emitted.

Not only do various sorts of motion give rise to varying sounds, such as the sounds peculiar to striking, to rubbing, to tearing, and the like; but also an almost infinite variety appears to exist in the manner of moving inherent in various substances, and each substance seems capable of transmitting to our ears, and that through an intervening medium, an impression of its own peculiarity in this respect. Even the shortest, sharpest sounds, will in many cases convey to us the impression of the material from which they were caused. The crack of a whip, the blow of an iron hammer, the blow of a wooden mallet, and the crack of a rifle, are all readily distinguished when heard, though they are all instantaneous. To this subtile peculiarity is due the greater part of that infinite variety existing in the sounds that meet our ear, and it is usual to distinguish those properties of certain sounds which are traceable to its influence, as the *quality* of those sounds; variations in quality and loudness are the principal properties that seem to be appreciable in sudden sounds, or even in those irregularly or slowly repeated.

By the loudness of a sound is meant the force with which it strikes upon the ear, and this force seems directly to depend upon the force of the impulse to which it owes its rise, modified by the distance the sound has had to travel, or the obstacles it has had to encounter in reaching the hearer.

Continuous sounds have another quality different from loudness, yet liable to be confounded with it, that of *intensity*, by this is meant the concentrated penetrating character that belongs to all very pure sounds. Intensity seems only to attach to prolonged sounds, and is probably partly due to the force and length of each separate impulse of which they are made up, and partly to the perfect equality and equable recurrence of these impulses. The difference between intensity and loudness is well illustrated by comparing the sound of a good bell with that of a gong, selected to match it; the two when struck will appear to the striker equally loud, but the voice of the bell being more intense than that of the gong, will be heard to a much greater distance.

It is possible not only to procure different notes from two perfectly similar strings, by stretching them more or less tightly, but conversely to cause two dissimilar strings, supposing the difference between their length and weight not to be very extreme, to sound two notes of the same pitch. Supposing these strings to be of the same material, and therefore to furnish the same quality of sound, it would be presumable beforehand that the notes so sounded would be identical, and yet upon experiment a difference would be perceptible which would not lie either in pitch, loudness, or quality, but in volume and intensity. The note produced by the heavier string under the greatest tension would have a more penetrating quality than that of the other. It would be heard through a greater number of obstacles by a distant hearer, and would more powerfully impress those near than would the note from the lighter string.

The homogeneity of the vibrating body appears essential to its uttering an intense sound. The bell here again affords a good illustration, for it is well known that any flaws, or any inequalities in the composition of a bell, materially diminish its power.

Volume or amplitude is a quality of sound that it is more difficult to define in precise words than almost any other; it really means a large quantity of sound, which at the same time may or may not be loud, and results from one large substance, or many substances together, giving forth sound;

thus there is more volume in the notes of a double bass than in those of a violin, and more in the singing of a chorus than of a single singer.

Pitch is that variety in sounds which we describe in ordinary language as their being low or high, grave or acute, and the full consideration of it belongs to the following section. In continuous sounds this is due to the greater or less rapidity of the repetitions that compose them, but in other sounds there is a variety of pitch that must arise from some quality of the material itself, or the mode of eliciting its sound. To account for the pitch of sudden sounds, Savart suggests that perhaps repeated impulses or vibrations accompany all audible sounds, even the very shortest.*

The distinctness of sounds requires no description; it is, however, desirable to point it out for separate notice, because loss of distinctness is more frequently produced by buildings than any other injurious effect, and because to some extent in music, and to a great extent in speaking, distinctness is indispensable to the satisfaction of the hearers.

As regards noise Chladni, perhaps the best authority, admits that nothing certain is known as to its nature, any more than as to the nature of tone (or quality); he conjectures, however, that noise may result from entirely irregular impulses or agitations of the air, and that tone may be pure musical sound, varied by the occurrence along with the regular vibrations which constitute a musical note, of a certain amount of irregular or uneven agitations.†

Music depends entirely upon the relations that subsist in pitch between different sustained sounds or notes, and upon the momentary impression of one note or chord resting in the memory or the ear when the next is sounded. It is not isolated notes, of however fine a quality, but the succession of such sounds or the blending them together that forms music; hence in all music there must be some relation between each note or chord, except the first of a passage and those that have gone before, and some recollection of them. In articulate speech, on the other hand, each syllable is a distinct concatenation of two or more sounds only, and though it may be combined with other syllables to make a word, yet it in no way depends upon them for its own completeness.

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* Institut. No. 285.

† Traité d'Acoustique, sects. 1 and 31.

Hence upon no music, however rapid, can the consequences of prolonging the impression of sounds beyond the time that they themselves actually last, exercise so injurious an influence as upon spoken words, where each syllable ought to be heard distinctly and separately, and where only the combinations of letters that go to form single syllables could at all bear to be run together.

It is foreign to our purpose to give here any analysis of the organs of speech, or of the different sounds they can utter; we can only indicate this broad difference existing between music (including singing) and speaking, because it will be afterwards shown that a degree of resonance is advantageous to music rooms, which, on account of its tendency to injure distinctness, would be quite inadmissible in such apartments as are required for speaking.

(3.) "When rapid successive impressions on the ear follow at regular intervals, a continuous sound is heard (the pitch of which depends on the frequency of the repetitions). Such notes are, in all but exceptional cases, caused by the vibrations of some elastic body."

"If," says Dr. Arnott, "a wheel with teeth be made to turn and to strike a piece of quill with every tooth, it will, when moved slowly, allow every tooth to be seen and every blow to be separately heard, but with increasing velocity, the eye will lose sight of the individual teeth, and the ear, ceasing to perceive the separate blows, will at last only hear a smooth continuous sound called a *tone*, of which the character (*i.e.* pitch) will change with the velocity of the wheel." *

---

* Elements of Physics, Part III., sect. 4.

In this instance, and in some few others, the sound is produced artificially, but in nature, nearly if not quite the whole of the continuous sounds that meet our ears are due to the vibration of elastic bodies; and when, as in the ring of a bell, or the note of a harp-string, the sound continues for a length of time after apparently only a single exciting impulse, it is really caused by the series of separate impulses rising in the vibrations of the metal or the cord, and conveyed separately and singly to the ear, along whatever medium is employed as a conductor.

A wire or cord stretched between two fixed points, is the most familiar instance of an elastic body in a condition to vibrate. Should it be pulled aside and then let go, it will be seen not only to return to its straight position, but to fly to nearly as far on the other side as it had been originally drawn to this side; and it will continue to move to and fro for some time; each journey traversing rather less space than the last, and moving less rapidly, and consequently with less force; but as long at its length and its tension remain unaltered, its vibrations will all occupy the same space of time. Consequently a continuous note will be heard, the pitch of which will remain the same as long as the vibrations continue, but the loudness of which will diminish as the motions of the cord become less vigorous; while the quality of the sound will depend, as has already been observed, upon the material of which the vibrating cord has been composed.

Should the cord be shortened, or should it be stretched more tightly, its vibrations when excited will become more frequent, and the resulting sound will have what is called a higher pitch. The same result would be obtained could the cord be rendered lighter. The strings of a harp present an illustration of what has just been said—those that sound the lowest notes will be found to be both the longest, the loosest, and the heaviest, while the strings that when touched give the highest notes are the thinnest, the shortest, and the most tightly stretched.

Many of the bodies capable of conducting sound are also capable, when properly set in vibratory motion, of emitting it; and nowhere is this so remarkable as in the air, for as the air is the vehicle of sound the most familiar to us, so is it also employed in the production of the most important, and by far the most beautiful sounds in nature.

If a column of air in a pipe closed at the ends receive an impression that sets it in motion, a pulse will be excited in it that will travel to and fro from end to end of the pipe, causing at each extremity alternate dilations and compressions of the contained air, while in the centre no variations in its density, but considerable movement to and fro of its particles, will exist. Should such an impulse, recurring at frequent intervals, be kept up by any suitable agitation, the result of this movement going on in the pipe, will be that a sound will be emitted, the pitch of which is proportionate to the distance from end to end of the pipe: because as motion can only be transmitted at a certain speed through air, it will require a definite time for the pulse to make a journey. Each journey will cause a distinct sonorous impulse to be emitted, and upon the number of these journeys in a second depends the pitch of the sound heard; just as when a string is vibrating, the pitch of its note depends upon the number of excursions of the string in a second.

If the agitation in the pipe be made more intense, a point will be reached at which the air will divide itself into two equal lengths—the point of separation being technically termed a node—and in each half of the pipe vibrations will go on precisely as would occur in a pipe half the length. As these pulses have only half as far to go, but travel at the same unalterable speed, two of them will be heard where one was before, and the note bearing the relation to the first one of 2 to 1; that is to say, the octave above it will become audible. The next note that can be produced by more vigorous agitation is that following the division of the pipe into three lengths by the establishment of two nodes, and will be the twelfth above the key-note. Pipes so closed are not in common use as musical instruments, but are in use as organ-pipes, and on any "stopped" organ-pipe the phenomena we have described can be produced by blowing through it with greater or less force. If, however, this pipe were cut in two in the centre, and half taken away, the agitation being kept up, the result would be that the same fundamental note would still be heard; the distance from the open end of this half pipe to its closed end *and back again* now becomes the measure of the journey each pulse has to make, and this it will be seen at a glance is the same as the length of the original pipe; consequently, a pipe open at one end must only be half as long as one open at both ends, to give the same notes, or if of the same length will give a note an octave lower. This form of a vibrating column of air is familiar enough to us in nearly all musical wind instruments — the flute, or the clarinet for instance, and in many organ-pipes. A column of air in a tube open at both ends can, with some difficulty, be made to emit sound. When it does so, a node is formed in the centre, and its pulses are consequently only half as long as those of the pipe stopped at one end, its note is therefore an octave higher than that of such a pipe, but the same as that of a pipe of the same length stopped at both ends.

In some musical instruments, like the clarinet, a "reed" is employed, and in others, like the flute, merely a column of air blown against that in the tube, to keep up the sonorous agitations,* and in most there are holes pierced, by uncovering which nodes are caused to form themselves which alter the length of the internal undulations, and, consequently, the pitch of the note given out; while, if the degree of force with which the instrument is blown is increased, a series of notes, one or even two octaves higher, is obtained. The pipes of an organ present the simplest, and the tones of the human voice the most complicated and subtile, instances of musical notes resulting from the vibrations of a column of air. Such vibrations at times occur in columns of air of vast size—such as that contained in a church or a room—and in that case, when a sonorous agitation is excited by any cause, a note distinctly recognisable by a good musical ear becomes more or less clearly heard; this is known as the "note of the room," and is a matter of frequent observation.

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* No doubt the passage of the air through those musical instruments which are blown into from one end tends to alter the resulting sound; but the influence of this circumstance on the pitch is but slight, and it is chiefly of advantage in the impulse it gives to the sound when it leaves the tube in which it is produced.

It must not be forgotten that a subdivision of the primary undulations just like this division of a vibrating column of air by nodes into smaller portions, constantly takes place in vibrating cords, and in almost all vibrating bodies; and further, that two or three distinct sets of vibrations can coexist in the same body, and, in fact, almost invariably do establish themselves, so that a person of acute musical ear can almost always detect in the vibrations of a cord, or still better in those of a bell, not only the fundamental note due to the dimensions, weight, and tension of the cord or the bell, but also the note an octave above it, together with the twelfth, and even the sixteenth or double octave. These notes are called the harmonies to the principal note.

An elegant instrument has been invented for measuring the actual number of vibrations in a second in any musical note; it is called the Sirène, and consists of a wind-chest, kept filled with air by proper bellows, and having an opening in its lid for the escape of the air that is blown into it. Over this opening a disc is fixed, pierced with a series of holes and mounted on a centre, so that when the disc is turned, each hole in succession will pass over the opening in the wind-chest, which the disc at other times closes, and thus let out a puff of wind; and as machinery is applied by which any required number of rotations per second can be given to the disc, it is possible to obtain any desired number of shocks on the air per second. The Sirène produces distinct, clear notes, capable of being compared with the notes of any musical instrument; and by this instrument it has been determined that the A on the treble cleff requires 880 single vibrations of a string or other sounding body, and that the compass of the human voice ranges from notes requiring 396 vibrations up to 2112 per second. The ordinary range of sounds audible to the human ear was stated by Euler to extend from a range of 30 vibrations of an ordinary cord, up to 7552 per second. By care, however, it has since been found by Mons. Savart to be possible to produce audible notes having as few as 14 or 15 single vibrations in a second, and up to as many as 48,000.*

The perception of a single musical note by the ear may be compared to the impression made on the eye by a series of equidistant dots ranged in a line. If two notes of different pitch, sounded together, are represented by lines of dots placed above one another, we shall perceive that where the dots bear a numerical relation to one another there is a symmetry in the appearance of the two lines, which does not occur otherwise. Similarly in music, when two notes are sounded together, the concord is pleasing if the number of vibrations in one bears some very simple numerical relation to the other, so that every second or third, or fourth, impulse of one note will coincide with one of the other note; and the more simple that relation, the more complete the concord. Thus, the octave of any note, which is a note so much allied to the original as to be held to be a repetition of it, contains always exactly double the number of vibrations; that is to say, if there are four vibrations of any note in the hundredth part of a second, the string sounding an octave above that note will have eight vibrations in the same time.

The next most consonant interval is the fifth, and in this the vibrations bear the relation to one another of two to three, or four to six; that is to say, starting as before from four vibrations in a given time, the note a fifth above that will give in the same time six vibrations.

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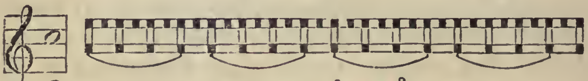
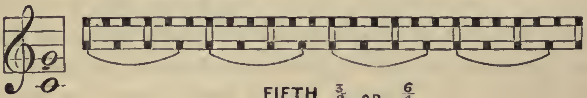
* Pouillet, Liv. v. chap. 2, sects. 36, 38; Somerville, pp. 150, 151.

The vibrations of the notes of a major third stand to each other in the less simple relation of four to five, and accordingly this interval, though consonant, is not so perfect in accordance as the other two referred to.

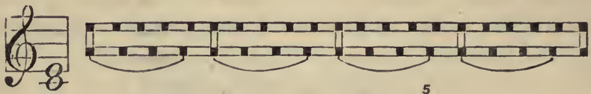
Dissonant intervals are those where the vibrations will very seldom coincide; as, for example, the seventh, where the vibrations stand in the relation of fifteen to eight, so that the coincidences between them occur but rarely; and the less simple the numerical relation between two or more notes, the less harmonious will they be when sounded together. By thus following out the indications given by the numerical values of different notes, the theory of music can be



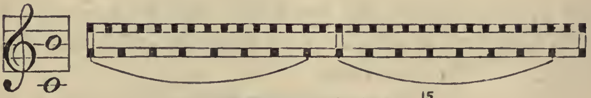
OCTAVE $\frac{2}{1}$ OR $\frac{8}{4}$



FIFTH $\frac{3}{2}$ OR $\frac{6}{4}$



MAJOR THIRD $\frac{5}{4}$



SEVENTH $\frac{15}{8}$

Fig. 1.

analysed, and, to a great extent, explained. Those who wish to pursue this subject will find it ably investigated in Herschel's treatise, Encyc. Metr. sec. 208 to 261.

Very elaborate inquiries and most beautiful experiments have been instituted on the modes of vibration peculiar to different substances and differently-shaped bodies, such as plates, bars, strings, rods, or the air in tubes, to show the relations between their movements and the sounds that can be obtained from them; in fact, vibration or undulation is so intimately connected with sound that the one is looked upon by scientific men as almost inseparable from the other. It is not, however, essential to the practical application of acoustics to buildings that this investigation should be entered upon, notwithstanding that it is one of the most elegant, beautiful, and interesting, but at the same time one of the most subtile within the range of physical science.*

PROPAGATION OF SOUND.

(4.) "Sound is conveyed most frequently through the atmosphere, but nearly all bodies will transmit it."

We are so accustomed to hear through the atmosphere, that sometimes it has been held that the presence of air was indispensable to the production or propagation of sound: this, however, is not strictly true. Air within the cavities of the ear is indeed the usual medium through which the sound travels from the outer ear to the tympanum, though the bones of the head sometimes conduct it; but in many cases the sound from the place of its production till it actually reaches the hearer, traverses only some solid or fluid conductor, as, for example, a bar of metal or a log of wood.

Any medium, whatever it be, which conveys the sensation of *motion* to the ear, conveys the sensation of sound; and those substances through which sound penetrates with difficulty—as, for example, sand or felt—are just such as are least fitted to convey unimpaired the impression of a sudden rapid movement, the converse being true also.

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* Consult the works of Chladni, Savart, and Wheatstone, enumerated in the list of books of reference.

The air is that conductor of sound to which we are the most accustomed, and with which we have the most concern; but though the most familiar, it is neither the only nor the best transmitting medium. Sound is conveyed both more rapidly and to greater distances through metals, through water, or even through the earth. A remarkable illustration of this fact was afforded by an experiment of M. Biot on a cast-iron tube of large diameter, about 1000 yards long. On striking a blow at one end of this, the observer heard two sounds at the other, the first being that transmitted through the iron, and the second that transmitted at a slower rate through the air in the tube: careful observations showed that the sound traversed the iron at about ten and a-half times its speed in air.[*]

Colladon and Sturm, in their experiments on the Lake of Geneva, found that sounds made and heard under water were transmitted more rapidly than in the air, and to great distances, for they succeeded in hearing the sound of a bell struck nine miles away; but the sounds heard were very dissimilar to those the same bell would emit in the open air, being short, sharp, and harsh. Wheatstone's experiments with solid conductors demonstrate that they do not alter the sounds they convey.[‡]

"Solids," says Herschel, "if elastic, are equally well or better adapted for the conveyance of sound with fluids. By elasticity in a solid is not meant a power of undergoing *great* extensions and compressions after the manner of air or India rubber, and returning readily to its former dimensions; but rather what is commonly called hardness in contradistinction to toughness, a violent resistance to the displacement of the molecules *inter se* in all directions.

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[*] Mem. de la Soc. d'Arcueil, Tome II., p 403.

[†] Journ. of Royal Society, 1831.

Thus the hardest solids are, generally speaking, the most elastic, as glass, steel, and the hard, brittle alloys of copper and tin of which mirrors are made; and, in proportion as they are so, they are adapted to the free propagation of sound through their substance." Encyc. Metr., sec. 104.

(5.) "Sounds traverse the air at an uniform rate of speed, but with a constantly diminishing strength; they naturally follow a straight course, but their direction is liable to be modified by the objects they meet; they are subject to be reflected, deflected, conducted or absorbed."

The rate of speed of sounds in the atmosphere, it is proper to observe, depends upon the density of that medium, and therefore is subject to vary with the fluctuations of temperature and humidity. It is, however, invariably the same for the same density, and therefore may be considered as practically uniform; the actual velocity has been repeatedly and very carefully measured, and the best experiments show that in dry air, and at freezing temperature, sound travels at the rate of 1090 feet or 363 yards, and at 62° Farenheit, 1125 feet, or 375 yards in a second, which latter rate equals 9000 feet in eight seconds, or $12\frac{3}{4}$ miles in a minute, or 765 miles in an hour.

Where a sound is travelling through open space, especially if it be one that has no particular initial direction imparted to it, it rapidly decays as it becomes more and more extended, and ultimately it ceases to be audible. It will be readily understood that this must be the case, because the surface over which the force of the original impulse is spread is constantly widening as the distance from the centre increases, so that, as the sound becomes more and more attenuated, the quantity of it which enters any given aperture, as, for instance, the opening of a human ear, or a hearing trumpet, will be proportionately weaker. Supposing, for instance, that a sounding body were completely enclosed in a hollow ball, the entire surface of which measured 10 square inches. If a hole of a square inch in surface were opened, an ear listening at that opening would, neglecting echo and other disturbing causes, hear one-tenth of the whole sound emitted; but supposing it transferred to a larger sphere of one hundred inches surface, an auditor will now only hear through a hole an inch square one hundredth part of the total sound, and will require to collect through a hearing trumpet the sound escaping through ten such holes before he hears as loud a sound as at the nearer point. Herschel, after an investigation of this subject, observes:—"We conclude, then, that the intensity of sound decays in receding from its origin, as the square of the distance increases. It is exceedingly difficult to subject this law to satisfactory experimental tests."

Where the lateral dispersion of sound is prevented, as in a speaking-tube, for instance, the decay takes place very slowly, and is due principally to the mere weight of the air, and the gradual loss of power from that and other obstacles.

The transmission of sound, as has been already stated, takes place through a great variety of substances, and the mode of its passage through all of them, the atmosphere included, is not dissimilar to that by which any other physical impulse is conveyed.

If a number of billiard balls be placed on a table, ranged in a straight line, and touching one another, the force of a smart blow in the direction of that line will be conveyed through the whole series of balls, and will reach the last one, which will fly off much as it would have done had it been itself struck.

It is easy to perceive that, rapidly as the impulse must have travelled, it really did occupy some space of time, and did pass through all the balls in succession, and that each in turn was subject to its influence and more or less compressed by it, and then having transmitted the impulse to the ball adjoining, recovered entirely its normal condition. Now, if we can consider these balls as particles of matter arranged in a straight line between any sounding body and the ear of an auditor, we have a very simple illustration of what actually occurs in every instance of the transmission of sound.

Supposing, further, an infinite number of such lines radiating through a vast series of balls, and that an impulse not acting along one line, but along the whole series of lines at the same moment, and with the same force, were to be excited, we can conceive that as on every one of the radiating lines, the transmitted impulse would be at any given moment, at the same distance from the centre there would be constantly a circle of balls under momentary compression, and this circle would at each instant become a larger one.

This too, it can be readily understood, is actually the case with the particles of air or of any other fluid medium that surrounds a sounding body; and this zone of compression, which goes extending further and further away into space, is usually called a *wave* of sound, just as any line along which the particles become one after the other successively compressed is called a *ray* of sound.

This illustration has designedly been preferred to the commonly adduced, and on the whole correct, example of waves on the surface of still water, forming rings that go constantly widening away from any point where a disturbance occurs. These waves appear to have been so often compared to sound-waves that the essential difference between them is forgotten. The water-waves are zones of up and down motion, spreading over the *surface* of a fluid. The sound-waves in air are hollow spheres, of alternate compression and dilation, extending through its whole substance; a displacement of particles occurs, it is true, but it is only a very slight one, and each undulation is completed by the medium returning to its original condition, and all its particles resuming their original place, such movement as has taken place having been, however, not up and down, as is the case in the surface waves of water, but to and fro. A wave of sound, even the most powerful, is to be considered not in the light of an actual displacement of the substance of the medium, but as a rapid passing through it of a momentary change of condition affecting each portion that it reaches for an infinitely short space of time, and then passing beyond and leaving quiescence behind it.

If this be a correct view, it is not difficult to understand how, with the most perfect quiescence of the air as far as the eye or the outward sensations can judge, the most powerful impulses may be in the act of transmission, like a current of electricity passing along a galvanic wire. If this zone of compression in the atmosphere has to pass through any thin medium, itself elastic and stretched like the head of a drum, and then is received by a continuation of the original atmosphere, it may be expected in its transmission to affect this interposed body very sensibly; and this is precisely the arrangement which has been provided in the human ear for receiving the impression of all impulses of sound. Infinitely inferior in sensibility to this beautiful apparatus as is the sense of touch in our fingers, it is nevertheless practicable to render the vibrations of even an ordinary human voice sensible to the touch by collecting them together on an elastic surface. If a broad sheet of glass or a glass shade be held in both hands, and slowly raised to the level of the mouth while speaking, as soon as it rises high enough to catch the vibrations of the sound it will be felt to tremble with every word spoken.

As a correct conception of the nature of the propagation of sound in the atmosphere is of fundamental importance, it may be well to add a further illustration of the nature of a sound-wave, slightly abridged from the lucid explanation given by Pouillet.*

Suppose, then, we have a horizontal tube open at the ends *t*, *t′*, say 10,000 feet long, and one inch in diameter, filled with air at an uniform temperature and pressure, and that a close-fitting piston *p* can in a second of time be pushed from *p* to *s*, a distance of one inch.

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* Cours de Physique, Liv. v. chap. i.

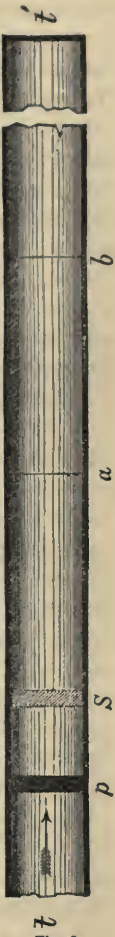

Fig. 2.

During the passage of the piston from *p* to *s*, the condition of the air in the tube undergoes certain modifications. To investigate these, let us suppose all the particles of air to remain fixed in the position and condition they occupy at the moment the piston stops at *s*.

Had the tube been occupied by a perfectly hard body, an inch of that body would have projected from the end of the tube at the moment the piston had completed its inch of motion; but there is no *perfectly* hard body, and air is a very fluid and very compressible body; consequently, when the piston pushes upon one end of the column of air the other end cannot obey at the same instant. Time is necessary for the impulse to arrive; and with such a length of tube as we have supposed, it can be safely affirmed that no particle of air has left the open end *t′*, while the piston has travelled to *s*. The air in the pipe is therefore *compressed*, for it occupies an inch less space than it did before. Further, it is unequally compressed, for as the impulse has not yet reached the mouth of the tube, only a portion of the air is as yet affected. Let that portion be supposed to reach to *a;* then the air between *a* and the extremity *t′* is in its normal condition, but the space between the piston and *a*—namely, *s a*—is a wave of sound whose length would be described to be equal to the distance from *s* to *a*.

Now, let us examine the condition of this wave *s a*, and for this purpose let us suppose it divided into slices parallel to the piston. Two things are obvious about it—

first, that all its particles have been compressed; secondly, that all of them have received an impulsive motion away from the source of motion, the piston.

It is clear that the different slices of the entire wave cannot all of them be in the same state; that one, for instance, nearest to *a* can have only undergone a very slight displacement and a very slight compression, for the disturbance has but just reached it. The first slice again, that at *s*, nearest the piston, is already on the point of reaching a state of rest, for we are now investigating the phenomena at the moment the piston stops; and as this slice has no longer any motion, so also it is under no compression—it has already transmitted all it had. On the other hand, those slices towards the centre of the wave are at once subject to the greatest compression and the most rapid motion.

Supposing now the piston to remain at *s*, let us see what will happen during the moments of time that follow its arriving there. The air compressed for an instant between *s* and *a* will not remain in that state; after a certain time, the extremity of the pipe being open, the excess of air will leave the pipe and the whole column return to a state of repose. The compression and the displacement will therefore be propagated onward to the mouth of the pipe, and the mode of propagation will be as follows: by the end of the first *instant* of the second *second* the compression will have seized upon a first slice to the right of *a*, and at the same instant an equal slice adjoining the piston will have recovered its repose; by the end of the second instant a second slice in front of *a* will have been seized, and a second slice in front of the piston will have recovered its repose, and so on till at the end of the second second the air between the piston and *a* is entirely at rest, having recovered its normal condition; that between *a* and *b* is compressed, and that between *b* and the end of the pipe still remains undisturbed; and further, the different slices of air between *a* and *b* are in analogous conditions to those of the corresponding slices a second before between the piston and *a*, so that the wave advances, so to speak, as a whole, preserving its various characteristics in its entire length, just as we have previously described the pressure advancing through a series of billiard balls.

It would be easy to show that on drawing back the piston from *s* to *p* a reversed movement would take place, the wave being now a rarefied wave instead of a condensed one, of exactly the same length as the condensed wave, and capable of being divided into slices like the other, with the uniform result in each case, that in the centre of the wave the movement and rarefaction will be at their greatest, and towards the ends they will diminish.

All ordinary vibrations, as of a musical string, for example, propagate alternately a condensed and a rarefied wave, and it is customary to consider that these two waves together make one complete undulation, just as two excursions of the string are required to make one complete vibration.

It will be noticed that these undulations have the property that the point of greatest movement and greatest compression or dilatation are the same. These are the undulations that *convey* sound. When a body of air is in vibratory motion, so as to *emit* sound, its waves are, as we have already had occasion to notice, on page 10, in just the opposite condition; the point of greatest motion is the only one where the density remains unchanged, and the points of rest, or nodes, are those of greatest compression and dilatation.

The course taken by undisturbed sounds is a direct one, and though some of them radiate to all sides from a centre, the large majority have an initial direction impressed upon them, and travel much further in that direction than laterally. We are familiar with this fact, because on our own speech we impress a direction of this nature, so that we are always best heard when our hearers place themselves directly in a line with the mouth.

That sound is subject to be reflected is a matter of familiar experience, from the constant recurrence of the phenomenon of echo. The behaviour of a billiard ball, to return to a former illustration, driven against the side of the table from which it will rebound, will present a resemblance to that of a ray of sound striking against an obstacle. To see what actually occurs, we have only to suppose that the end of the pipe, $t t'$ in the last illustration, is closed instead of open. The consequence of that would be, that, when the front of the wave had reached t', it would be unable to advance further; the compression at its centre, n, would, however, be propagated onwards, till in half a second the further progress of the wave was arrested entirely. When that occurs, the point of greatest compression will be at t', the closed extremity of the pipe, while the air between m and n will have fallen into repose. This condition of things will, however, be but momentary, the reaction of the compressed air will immediately originate a reflex motion, which will proceed from n back towards m; and at the expiry of the second half-second the wave will have resumed its original length, only it will now be upon its return journey from the stopped end back towards the piston that originally excited the motion.

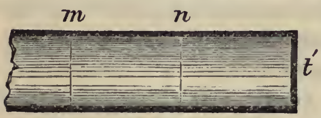

Fig. 3.

Sounds are also subject to deflection, that is to say, if in their course they encounter an obstacle, they have a tendency to spread after having passed it, and thus to encroach upon, and after a time destroy, the sound shadow. So that supposing A to represent a person speaking towards a thick wall, and the radiating lines to represent the rays of sound from his voice, so much of the sound as is not intercepted by the wall will

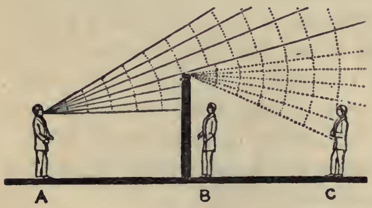

Fig. 4.

have a tendency to spread downwards, as shown by dotted lines; consequently, although a person directly behind the wall at B may perhaps hardly be able to hear at all, one further off, as at C, will certainly hear pretty well, notwithstanding that the direct rays of sound, shown by the full lines, pass much further above the head of C than of B. This deflection however, appears to take place to a very limited extent in sounds that have one direction impressed upon them, and are travelling in parallel, not in radiating lines.*

The experiments of M. Colladon, on the lake of Geneva, show that sounds propagated under water are not deflected to anything like the same extent as in air, or, in other words, that the acoustic shadow will be much stronger under water than in the atmosphere.

Besides the regular dispersion of sound and its absorption and interruption, there seem to be agencies at work causing variations in its transmission through the air that cannot be altogether accounted for. It is matter of common observation that sounds are heard more clearly at night than in the day, and this even in tropical climates, where the night is more alive with animal life than the day so that the absence of disturbing sounds cannot be the sole cause of the greater facility of hearing.

It is not surprising that sounds should be heard far on a frosty day,† as the greater density of the air would render this probable; and that fogs, falling rain and snow should obstruct its free propagation can easily be accounted for by the fact that the air would not only be less dense than ordinary at such times, but also less homogeneous, in consequence of having aqueous particles of one sort or other mixed with it. It remains, however, to be explained why the sound of a distant bell should, at short intervals on the same day, vary so much during the time of one experiment, conducted in still weather, as to be alternately almost lost and powerfully audible, so that at one time it seemed more distinct and at another time less distinct than a second bell much nearer the experimenter; or why sounds, though audible to a much greater distance with the wind than against it, yet proved audible across the wind to a still greater distance than either up or down it. These phenomena are, however, reported on by Mons. F. Délaroche, in a paper on the influence of wind on the intensity of sound,* and appear to have been so accurately and repeatedly observed by him, that there does not seem ground for their rejection.

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* In one of Saunders's experiments on deflection, a result was obtained not quite in accordance with common experience; but the conditions under which the experiment was made appear to have been rather exceptional.

† Herschel, Encyc. Met., art. "Sound," sec. 21, 22.

It may be noted that humidity in the atmosphere, not condensed into fog or haze, is held to favour the propagation of sound. Admiral Fitzroy † remarks, "Remarkable clearness of atmosphere near the horizon, and what is called 'a good *hearing* day' may be mentioned among signs of wet, if not wind, to be expected."

As regards the conduction of sound, Herschel observes: "It is evident, without entering into any nice theoretical considerations, that a mechanical impulse, of whatever nature, impressed on any portion of the air or other medium, whether fluid or solid, and thence communicated to the surrounding parts, if allowed to spread in all directions as from a centre, must reach every more distant point with an energy continually less and less, because the same quantity of motion is communicated in succession to a larger and larger sphere of inert matter; but if only allowed to spread in certain directions, its diminution will be less rapid in proportion as the quantity of matter successively put in motion increases less rapidly. Hence a sound might be expected to be conveyed with less diminution along a wall than in the open air, the trough or angle between the wall and the ground forming, in fact, two sides of a square pipe."

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* "Annales de Physique," tom. i., p. 176, A.D. 1816.

† "Barometer and Weather Guide," p. 15, A.D. 1859.

An instance of the conduction of sounds to a surprising distance where all lateral dispersion is prevented, occurred in the experiment of Mons. Biot, on the iron pipe already referred to, for through it he found he was able to hear the lowest whisper from a speaker more than one thousand yards away, in the night-time; in the day-time it was not found so easy to communicate.

A remarkable instance of the conduction of sound along smooth walls occurs at the Whispering Gallery at St. Paul's, where a whisper, spoken by any one with his face turned towards the wall, and close to it, is conveyed at the same time in two opposite directions along the smooth surface of the interior of the circular drum below the dome. The two conducted sounds, each having accomplished half the circuit of the gallery, arrive at the same moment at the point H, exactly opposite the speaker at S, and a listener at that spot will consequently hear a sound twice as loud as at any other part of the circuit. This phenomenon has been repeatedly, but erroneously, ascribed to reflection; its true source appears to have been first pointed out by Saunders.*

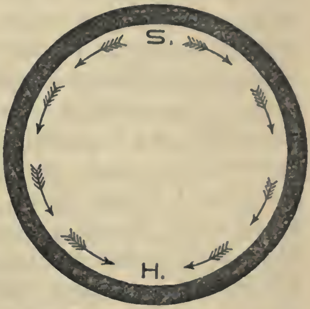

Fig. 5.

The absorption of sound is a phenomenon analogous to the absorption of light by a dark or black surface, or to the deadening of the motion of a moving body when it is received on a soft yielding surface.

The same substances which would most effectually destroy and least reflect the motion of any hard body such as a ball, propelled forcibly against them, will also most thoroughly absorb sound, and by destroying the undulations that propagate it prevent its further progress.

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* In his treatise on Theatres. See also Hutton's "Mathematical Dictionary," under the article "Whispering places."

6. "There is a great similarity between the laws that govern sound and light, but sometimes the propagation of sound in the atmosphere bears an analogy to that of undulations on the surface of water." This proposition is almost an amplification of the last one, but as it is of some importance, on account of its furnishing the architect with an analogy that may often be useful to him, it seemed right to give it a distinct place.

Sound in its uniformity of speed, and in its decay by radiation, resembles light; in its mode of deflection, reflection, and absorption, it partly resembles light and partly water. The way in which it can be conducted however bears no analogy to the movements of light, but resembles closely those of water, or other ponderable fluids.

Light, like sound, travels in straight lines from its original source, and it resembles sound in this also, that it is discovered to consist of distinct impulses succeeding one another and forming waves. Light, however, differs from sound in its travelling through an imponderable medium, whereas all sounds are transmitted through media whose weight, and consequent inertia, are always modifying the motions that they make; and if we watch the action of waves of motion *on* the surface of water, and bear in mind while doing so the distinction as well as the likeness that obtains between them and waves of sound *in* the air, we shall often observe the closest analogy between the two. In certain places waves of water are broken, in others they pass freely, in others they are reflected, and in others they are caused to change their direction. It is not perhaps too much to say that in similar positions waves of sound will always be similarly broken, or transmitted, or reflected, or deflected, as the case may be.

In the phenomena of reflection both analogies hold good. When a ray of light falls upon any polished body it is reflected very little diminished in amount or altered in quality. In all other cases, however, the light is considered to be partially absorbed, and the remainder is given off by different bodies in different degrees, each throwing off such rays of light only as indicate its own colour and absorbing the others, and every object upon which the light shines thus in turn irradiates light.

To a certain limited extent the same thing occurs with sound. It is also reflected by some bodies and irradiated in the form of sympathetic vibrations by others, and it requires a certain hardness of surface to do either. Whatever the essential difference between those surfaces that do, and those that do not reflect light may be, the distinction between bodies that merely reflect sound, and those that if they reflect it partially also reinforce it by sympathetic vibration, is that the latter are highly vibratory, and the former are not.

When light strikes any reflector at right angles to its surface, it is reflected straight back, and when it strikes obliquely it is also thrown off obliquely, the angle of incidence being always equal to the angle of reflection. In waves on water this occurs only within certain limits, namely as long as the waves strike the reflecting surface at an angle greater than from 30 to 45 degrees. But, as Mr. Scott Russell has shown, when they strike at a more acute angle than 45 degrees, they are not perfectly, and when at one more acute than 30 degrees not at all reflected, but seem to travel along the bank or other surface against which they had struck. Waves of sound act in a similar manner, and hence arises the phenomenon of conduction.*

REINFORCEMENT OF SOUND.

7. "Bodies capable of vibrating so as to produce any sustained sound, are ordinarily apt spontaneously to

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* See ante, p. 26; Euler, "Lettres à une Princesse;" Weber, "Wellenlehre;" Scott Russell, "Report on Waves," p. 54.

vibrate when a sound of the same pitch is excited near them."

This is true not only of such sonorous bodies as when excited give out a distinct musical note, but of others which cannot be said to have any sound peculiar to themselves. Bodies of the former class are set in sonorous motion only by such sounds as they themselves could emit, *i.e.* by their own fundamental note or its harmonics; bodies of the other class will vibrate in unison with any or almost any note or notes that are excited near them. These vibrations, which we may call *sympathetic* vibrations, are of great value in reinforcing an original sound, and adding to it a character that it did not naturally possess, and for such a purpose the second class of substances are the most valuable, and among them thin plates of wood pre-eminently so. It is quite true that bodies possessing a characteristic note of their own are more violently excited than others, when that note or its harmonics are given out by some sounding body in close proximity to, or actual contact with them, but then they will respond to no other note, while such a substance as a well-seasoned plate of fine thin wood will respond almost equally well to any note or to any simultaneous combination of notes. It is this property that renders such wood so valuable for the sounding-boards of pianofortes, for the bodies of guitars, violins, violoncellos, &c., or for the construction of an orchestra, and the floor, walls, and ceiling of a music-room.

It is the power of setting a large mass of wood in vibration that gives the *tone* to all stringed instruments, and it is a matter well understood that the variations which make one violin or one pianoforte to be so much more valuable for musical purposes than another, do not lie at all in the strings that are put into *direct* vibration by the musician, but in the qualities inherent in the reinforcing body which those strings throw into *sympathetic* vibration.

These vibrations are ordinarily communicated through the air, and referring to that mode of inducing motion, Herschel observes: "Just as a small pull, repeated exactly in the time of its natural swing, will raise a great bell, or a trifling impulse a heavy pendulum, so the molecules of the air in a state of sonorous vibration will impress on any body *capable of vibrating in their own time* an actual vibratory motion, and if a body be susceptible of a number of modes of vibration performed in different times, *that mode only will be excited which is synchronous with the aerial pulsations.*"* If, however, the exciting and excited body are in actual contact the induced vibrations will be the more vigorous, and they will even display an amount of motive power out of all proportion with the original exciting cause.

"To show this in a striking manner," says Pouillet, "it is only needful to connect a little tube of glass to a large beam of wood, and then to excite vibrations in the tube by rubbing it with a wetted cloth; at once the entire mass of the beam will enter into longitudinal vibration, lengthening and contracting itself; and an enormous weight acting by tension or by compression would be required to cause the same changes that a very light rubbing can excite." †

The most delicately sensitive bodies appear to be thin membranes stretched tight, and by the use of these, with sand sprinkled on them, M. Savart was able to explore the condition of the different portions of the air of a room and to make visible the agitations roused in it by sound. In this experiment he was obliged to produce sounds of great intensity, and obtained them by means of the reinforcement arising from the vibrations of air in a wide-mouthed vessel, which was capable of emitting a definite note, and in front of which was placed a bell having the same pitch. By an apparatus of this nature sounds of a surprising intensity can be obtained, showing that, suitably applied, a mass of air is a powerful reinforcing body. Such a body of air is not, however, near so manageable an auxiliary as wood on account of its aptness, when set in motion, to emit sounds having a definite pitch, regulated by the dimensions of the enclosing space; and although readily excited by those sounds or their harmonics it will refuse to vibrate in unison with more than a few notes.

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* Encyc. Brit., art. "Sound," sec. 169.

† "Elements de Physique," tom. ii. lib. 5, sec. 39.

The experiments of Professor Wheatstone on the transmission of sound to considerable distances, through wooden rods from musical instruments to reciprocating plates of wood, which in this way were made to emit a repetition of the original sound, are very striking, as showing the power of sympathetic vibration inherent in those plates.* His observations on similar vibrations in a column of air will serve to substantiate what has been advanced on that head, showing as they do that such a column when of fixed dimensions will only reciprocate sounds identical with its own note, or harmonics of that note.†

The seven propositions advanced on p. 3 have now been successively passed in review, and so much of the science of sound as seemed necessary to the immediate object of this volume has been introduced in illustration of those propositions. Through thus limiting the statement of the theory of acoustics, it has been found necessary to dismiss with merely passing allusion some of those phenomena that have attracted the most attention from investigators, and to omit altogether any mention of others. These omissions it is believed cannot in any way militate against the value of the work to the architect, as they relate to refinements with which in his practice he has no concern; but it is right to notice their existence, lest any should think that an outline of every department of the science had been here attempted, and left incomplete; this, it will now be understood, has not been the case.

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* Journ. of Royal Institution, vol. ii., 1831.

† Quarterly Journal of Science, vol. iii., p. 175, A.D. 1828.

SECTION II.

OBSTACLES AND AUXILIARIES.

In order to understand the nature and the effects of some of the principal obstacles and auxiliaries which buildings can present to the diffusion of sound (and it is only some of them that are patent enough to be ascertained and described), it seems desirable to establish some normal standard of what may be considered its natural diffusion. The nearest approach to this is no doubt presented by the open air on some perfectly windless day; and we have heard it expressed as a deliberate opinion by one of the greatest living authorities on acoustics, that there is no possible building equal to the open air for perfection of hearing. Of this perfection the ancient Greeks and Romans, enjoying as they did a climate eminently favourable to out-of-door life, made good use in their theatres and fora.

Supposing the speaker and the hearer to have some little natural advantage in their positions with respect to one another, from inequalities of ground, it is possible, on a perfectly still day, to address large multitudes in the open air with great success. If, however, the auditors be all on a dead level, with the speaker only as much raised above them as on any usual platform or other speaking-place, the number of persons by whom a person possessing a voice not above *ordinary* power can be clearly heard will be restricted, though it is rather difficult to determine, even approximately, to what number.

The experiments undertaken by Saunders, and described by him in his book on theatres, gave as a result that when a person was made to read from a book on a still day on an open plain, he could be heard 92 feet in front, 75 feet on each side, and 31 feet behind; and the line denoting "the extreme distance at which the voice could be heard every way," was that shown in the figure.*

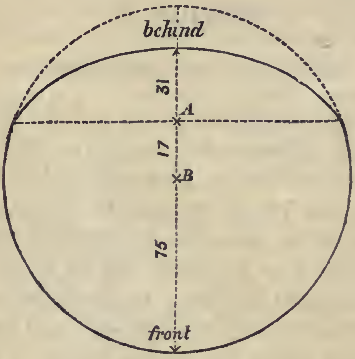

Fig. 6.

Sir Christopher Wren, however, in a letter on church-building, given in the "Parentalia," lays down as the standard that had guided him a much more limited range of voice. He says: "A moderate voice may be heard 50 feet distant before the preacher, 30 feet on each side, and 20 feet behind the pulpit, and not this unless the pronunciation be distinct."† And, in fact, it will be seen that, except under most favourable circumstances, the area over which a single voice can be heard by a single hearer moving from one part to another, can be no fair guide by which to estimate the size of such a crowd of persons standing on the same level as would be all able to hear well, for the persons nearest the speaker impede the distinct hearing of those who are further off, partly by the direct interference of their heads, partly by the unsuitableness of an uneven surface of human beings to conduct sound, and partly by the effect their warmth and breath have upon the atmosphere. It is not found in ordinary experience that a person speaking in the open air can be heard, in a crowd, so far as 92 feet, or to anything like that distance, unless he put forth a considerable effort; and it will probably not be far from the truth if we assume that if a cluster of as many persons as could hear distinctly were to form themselves round an individual of ordinary powers of voice (and it is necessary throughout this inquiry to disregard cases of unusually strong powers of voice as exceptional, and not a safe criterion), they would form a crowd somewhat similar in shape to the figure just given from Saunders, but probably not occupying more than 5000 square feet of ground. Were these persons to sit down, and in doing so to occupy each as much space as would be allotted to him in the seats of any ordinary public room, the number of the audience on the ground would be about one thousand, though two thousand or more could occupy the place standing; and this estimate agrees pretty closely with the limits assigned by Rhode in his admirable little book. He, taking Saunders's experiments as a guide, considers that a theatre will be within the range of the natural direct radiation of sound where no person is further than 70 feet from the speaker, and that such a theatre would seat two thousand persons; that is to say, about twice as many as could be seated on the level ground only.

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* Saunders on Theatres, chapter 2.

† "Parentalia," page 318.

Wren, in the document already referred to and which we shall again have to quote, expresses his belief that two thousand persons is about the extreme number that can see and hear in perfect comfort in a church. The churches that Wren built show, most of them, that he relied mainly on natural radiation for the diffusion of the voice in them.

Suppose now it be desired to shelter this seated audience of a thousand persons, by putting a roof over them and walls round them, we shall in so doing have altered in many ways the conditions under which they hear, and shall have introduced many conflicting agencies. As, however, they all could hear well before, it is plain that if we can only ensure that they shall in no respect be worse off than they previously were, we have done all that is necessary, supposing no larger number require to be accommodated.

It follows, therefore, that in buildings of moderate size, we are principally required to avoid the introduction of impediments to the free transmission of sound.

It may, however, be desired that a larger number of persons shall be addressed than ordinarily can hear in the open air; or if this be deemed impossible, then a larger number than could there hear without an advantageous disposition of the ground they occupied; or at least, taking the most favourable possible view of the capabilities of the unconstrained atmosphere, we may suppose that the desire is entertained to render it possible for as large a number to hear at all times, and in all weathers, within a building as could, under the most favourable circumstances, hear without one. If this is to be effected, the voice must clearly receive from some property or properties of the building assistance in character analogous to that which it receives from the stillness of the day and the favourable configuration of the ground, under the best natural conditions; and probably this assistance requires to be greater in amount in the case of buildings than in the open air, since it is likely that, however favourable the form or materials of the building, some prejudicial agencies will also be at work, which will require to be counteracted.

In one or two respects, however, all buildings, large or small, present advantages which ought to be pointed out. One essential difference between a building of almost any sort and the open air is that the hearers in a building are placed at a great advantage in consequence of the perfect *stillness* of the air, and the exclusion of any disturbing noise from without; while a second advantage may be held to be that the architect of any building for public purposes enjoys the opportunity of being able to place his audience and his speaker in any relative positions that he pleases. With these two considerations to set against the natural decay of all sound, and the inevitable disadvantages of almost all buildings, it is found that even in large structures the most important consideration proves after all to be not how to assist the voice, but merely how to avoid all impediments.

Extreme cases exist, on the one hand, of buildings of colossal size, in which sound can be heard so far and so well that it is indisputable that other circumstances besides the quietness of the atmosphere, and the relative positions of speaker and auditory, must have favoured hearing; and, on the other hand, of rooms sometimes not beyond the dimensions of ordinary dwelling apartments, where hearing is difficult, where reverberation is extreme, and even where certain musical notes cannot at all be sounded, proving that the apartment has exercised a powerful and injurious influence on sound. The experience of most persons will furnish instances of both these extremes, enough to justify the establishment of the following general maxims, which will form the basis of an attempt to classify the causes that operate upon the acoustic qualities of rooms.

I. Buildings always modify the normal diffusion of sound.

II. Buildings may present obstacles to the diffusion of sound.

III. Buildings may afford auxiliaries to the diffusion of sound.

(1.) " Buildings always modify the normal diffusion of sound."

This proposition is an almost necessary consequence of the preliminary observations of this chapter; and the truth is, that the moment a sound becomes surrounded by the multiplied conditions that affect it in a building—the disturbance, the resonance, or the echo that it may meet with—it is exposed to so many conflicting influences that it becomes very difficult for the man of science to do more than state very generally what results the conditions under which it is placed may reasonably be expected to induce.

Without further delay on this point, it is proposed to pass at once to the consideration first of the obstacles, and then of the auxiliaries that may exist in buildings; and afterwards to an examination of a few examples of those varieties of public and private buildings in which acoustic arrangements are of importance.

(2.) "Buildings may present obstacles to the production or propagation of sound."

The nature of these obstacles, the means of avoiding them and the remedies for them, where they exist, form, in the present state of acoustic science, perhaps the most important part of the inquiry, and possibly will always remain so; for it may be very safely asserted, that if an architect can only avoid all obstacles to the free propagation of sound in a building, he may be satisfied that, for ordinary purposes and within the limits of ordinary size, he is quite safe, and may trust to natural diffusion as sufficient to enable his audience to hear. It is only in cases such as concert-rooms, where special beauty of tone is required, or in rooms of very large dimensions, or in those where circumstances render it unavoidable that serious obstacles to the diffusion of sound should exist and be tolerated, that the auxiliaries which a building may be made to afford to sound require to be strenuously sought for; not that they ought ever to be lost sight of, but that the architect's first care ought always to be to avoid doing harm. We may do well always to recollect that the natural tendency of sound, truism though it be to say so, is to make itself heard; it is but little that we can do to assist it, and there is nothing in all our appliances that does not spring out of the nature of the sound itself. What we can do to interrupt and deaden, to disturb and counteract it, is, however, very much; and in this, as in many other branches of human activity, man's efforts are best directed when they simply refrain from impeding the ordinary course of nature.

The obstacles to sound may be conveniently classed under five heads, according as they act by decay, absorption, obstruction, reverberation, or echo.

1. *Decay.*—It is in no way peculiar to buildings that sound should decay in them in the manner explained at p. 17; on the contrary, they frequently prolong its progress in a particular direction by preventing it from spreading laterally; but it must never be lost sight of that it is the natural decay of sound as it proceeds further from its source, which imposes a limit to the possible size of an auditorium, and that this phenomenon it is which has to be counteracted by all the appliances in our power, when we wish to construct a hall which shall be of dimensions surpassing those of ordinary buildings, and yet remain acoustically useful.

2. *Absorption.*—Sound seems to be swallowed up by large unoccupied spaces, especially if above and behind the speaker, and by all soft dull surfaces within reach. The audience in any room absorb or deaden a great deal of sound by their clothing and the amount of uneven, soft, unreflecting surface they present. Of course this is just as much the case with an audience in the open air as in a room, but it becomes more perceptible in its influence on the voice in buildings than elsewhere. Similarly all curtains and hangings and carpets deaden and absorb sound.

This property, as shown by soft surfaces, is at times of value. Where there is too much resonance in a room, carpets or curtains may be advantageously employed to lessen it; in fact, to absorb the injurious excess of sound, and where there is an echo, a curtain judiciously hung will have the effect of deadening or stopping the sound before reaching the echoing surface. This expedient is well known, and often successfully employed; but carpets, as a remedy for excessive resonance, have perhaps not been so frequently made use of. An instance has, however, been mentioned to the writer of a large chapel in which an unpleasant reverberation existed, and which was cured by the simple expedient of covering all the passages and open spaces with matting. An analogous instance occurs in the new reading-room of the British Museum, where the floor is covered with kamptulicon, and the whole of the desks, &c., with leather, a precaution adapted not merely to prevent much noise from being made, but also to deaden the reverberation which, with an uncarpeted floor, would have been excessive. Under ordinary circumstances, however, the influence of a large audience is quite deadening enough, and carpets, cushions, and curtains should be absent as much as possible from a room for public speaking, unless, indeed, it has shown, when made use of uncarpeted and without drapery, extreme resonance, reverberation, or echo.

The amount of sound absorbed in large, ill-disposed, vacant spaces is very great, much more so than might be supposed; and injury from this cause can almost always be guarded against, if the danger is kept in mind during the designing of a building. An audience is a necessity, and carpets and curtains are often almost as much so, and if they absorb sound it cannot be helped; but a vacant space wrongly placed is never necessary, and always injurious.

It seems agreed by all writers, and confirmed by experience, that a very large amount of air above and behind a speaker, and which his voice has to set in motion, is injurious, and that a very large amount of air above the auditors may be also injurious, but in a less degree.* The old sounding-boards in many churches are probably of advantage as much by cutting off a great mass of the air in the upper part of the church from the direct influence of the speaker's voice, as by any other action they exert. The custom of placing the orchestra or platform of a public room in a recess, and bringing down the ceiling quite low over that part is now commonly adopted, and with good results, because it limits the volume of air over head.

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* Lachéz, page 54.

It is perhaps advantageous for a speaker to have a little space behind him, but that space should be much lower and narrower than the rest of the building.

If the voice should not be allowed to escape upwards, backwards, or sideways, immediately on its leaving the mouth, neither should it be allowed to waste itself anywhere upon a disproportionate height of space. One of the few points in which the majority of rooms good for sound agree, is that they are low in proportion to their width; in fact, to quote the words of a very good authority, "rooms for sound should be of *good* proportions, but rather low than high, and rather long than short." If the spaces about the speaker and above the audience be restricted, it seems probable that a very great extent of length might often safely be given to the auditory.

It may be proper to note that although for convenience we have included two agencies adapted to diminish the volume of sound under the head *Absorption*, a distinction will be often perceptible in their effect upon sound. Soft surfaces deaden and destroy its quality, but do not so much affect its distinctness; they are therefore more injurious to music than to speaking. Large spaces of air frequently themselves become resonant, and while they impair distinctness, may yet improve the quality of sound; they are, therefore, more objectionable where speaking is contemplated than for music, unless the instruments or the singer be deficient in power; and although rooms having these defects, like all rooms bad to hear in, are unpleasant to a speaker, yet the unpleasantness is not of the same sort. In the first-mentioned cases, *i. e.* when soft surfaces are in excess, a sense of oppression upon the voice, and a sort of deadness and heaviness are complained of; in the second case, the sonority possessed by all large masses of air often renders speaking or singing agreeable, and entices the speaker to make an unusual effort to fill the room, till after a short time he becomes wearied by the exertion required, and the consequent exhaustion, while the auditors are also dissatisfied, because though what they hear is spoken loud enough, and is really heard, it does not *distinctly* fall on the ear, but is heard encumbered and confused by secondary sounds that prolong each syllable into the next.

3. *Obstruction.*—The phenomena of light and vision, as has been already remarked, closely resemble those of sound and hearing, and the two mutually illustrate one another. This is emphatically the case with the obstructions to sound, for the simplest way of describing them is to say that whatever would be an obstruction to *sight*, is sure also to be injurious to sound, though not always to the same extent. Sounds travelling to a considerable distance are much more easily interrupted by an obstacle intervening between the sounding body and the hearer, than those that rise near at hand, for reflectors can be used with advantage close to the speaker which would quite destroy the sound in a distant part of a room, after it has lost a large portion of the force with which it was first emitted, and obstacles may be tolerated among the auditors near at hand, which would be much more injurious further off.

In every building intended for public purposes, provision should if possible be made that each person shall receive a direct and uninterrupted ray of sound, and shall have an equally uninterrupted *sight* of the speaker. To those at a distance this is especially important, partly because, as has just been observed, obstacles are more injurious to them, and partly because if they have any difficulty in hearing, a sight of the speaker will be likely to be of assistance.

The first published description of the mode of "setting out" the seats in any large building, so as to secure that each occupant of a seat shall have a direct uninterrupted hearing and sight, was given by Mr. Scott Russell, in a paper published in the *Edinburgh New Philosophical Journal* for 1839, and the same method has been more recently very fully developed in the little work of M. Lachéz already quoted. The seats must be ranged not as tangents to a straight line, but on a concave curve to be set out as follows. The position and height of the speaker and of the auditors occupying the first seat being determined, a line is to be drawn from the speaker's mouth touching the point where the top of the first auditor's head would come, and at the proper distance, say for example at 2 feet 6 inches back, the situation of the seat for the second auditor is to be marked, and on the line indicating the back of it a height of 1 foot 6 inches or less is to be set off upwards from the point where the ray from the speaker's mouth touched; this is to mark the position of the top of the head of the second auditor. By repeating this process, setting up eighteen inches at each seat, a series of points are found all ranged in a curve, to which Mr. Scott Russell has given the title of "the isacoustic," or equally-hearing curve. Each seat

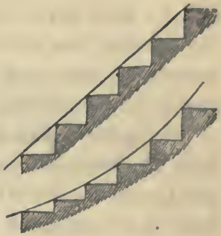
Fig. 7.

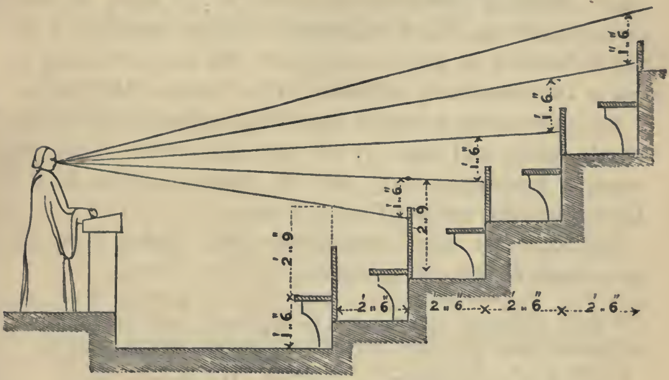

Fig. 8.

will be placed about 2 feet 9 inches below the mark indicating the top of the head of its occupant, and the floor on which each stands should be about 1 foot 6 inches lower still.* This curve, when the auditory is a good deal below the speaker, has the property of dipping down slightly at its commencement, and under such circumstances a flat floor might be substituted without serious disadvantage for part of the curve. The degree of steepness requisite will vary with circumstances, such as for instance whether it is essential for the auditors to look down on a table or merely to look up at a speaker, and the more space that can be allowed for each seat from front to back, the less inclination will be requisite. The Lecture Theatre of the Royal Institution, of which a plan and section are given later on, presents a floor elevated on this principle, but a much earlier example of at least an approximation to it exists in the Roman amphitheatre at Nismes, where the height of the seats increases as they become more remote from the arena.

In a number of churches built in Scotland for the Free Church party, immediately after the "disruption," Mr. Scott Russell's curve was adopted for the seats, and the arrangement was found satisfactory; and an example of its use in London is, or was previous to the fire, to be seen in one of the class-rooms attached to St. Martin's Hall, where it was particularly essential that the teacher should be distinctly heard and seen by all his class; and, lastly, an example familiar to many may be cited—the seats in the Handel orchestra at the Crystal Palace.

Subjoined are some illustrations from Lachéz † of the advantages of this arrangement.

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* These dimensions, especially 1·6 for face room, are in excess of what will suffice, where space must be rigidly economised. Lachéz prescribes :

	ft.	in.		ft.	in.
Back to back of seats - -	1	$11\frac{1}{2}$	to	2	$5\frac{1}{2}$
Height of seat - - -	1	$5\frac{3}{4}$			
Seats to top of head - -	2	$11\frac{1}{2}$	to	3	6
Face-room - - -		6	to	1	0

† "Acoustique et Optique," pp. 111-113.

Fig. 9 represents at A an auditory placed on a horizontal plane: the lines of sight are all parallel, and that of the last spectator, 40 feet off, falls over the professor's head at an elevation of 13 feet 6 in. If this auditory be placed on an inclined plane rising one in ten, an advantage is gained, but only a slight one, as shown at B; while by forming an isacoustic curve, as shown at C, without the back seat being higher than in the second instance, all the lines of sight are brought to one point. In the first two sections seeing and hearing must of necessity have been more or less imperfect; in the third they cannot fail to be satisfactory. Two sections are subjoined (fig. 10) to show the advantage, where the isacoustic curve is employed, of having the seats near the speaker low, where space permits. The same

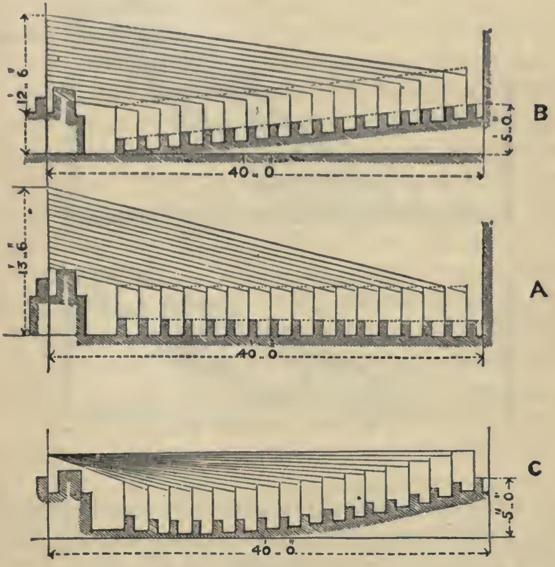

Fig. 9.

number of seats occur in both, but because in the first floor the front seat is only 2 feet 8 inches below the point of sight, while in the second it is placed 16 inches lower, there results a difference in the elevation necessary for the back seat of a range of only ten seats in all, of no less than 9 feet 6 inches.

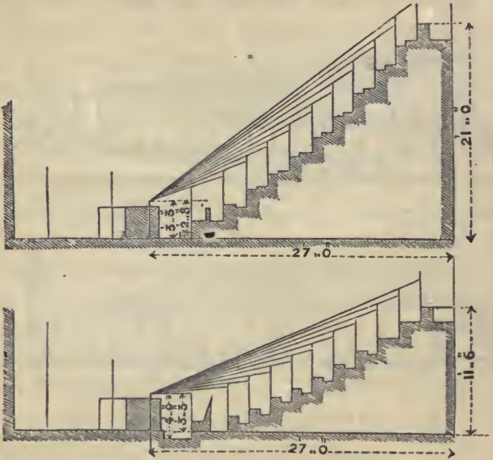

Fig. 10.

On this point Lachéz lays down the following maxims —"The more the object to be seen is elevated, and the less inclination do the seats for the auditory require, the more the seats for the auditory are elevated, the lower will it be possible to place the object to be seen.

"But the distance from the auditory to the object to be seen exercises a considerable influence alike upon the inclination of the seats, and the elevation of the point of sight." *

So far this disposition of the auditory has been considered by us merely with a reference to the procuring a direct ray

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* "Acoustique et Optique," p. 75.

of sound and line of sight for each auditor. A collateral consideration is pointed out by Rhode, who shows that the stepped arrangement of seats, especially where the building in which it is adopted is curved in outline, is eminently advantageous, on account of the small possibility that with such an arrangement any injurious echo can arise. After a reference to the error of those who suppose that sounds reflected back among an auditory from a wall behind them could ever be other than disadvantageous, he observes:*—"Here it is proper to inquire whether in a theatre of curvilinear shape in which the seats are arranged as steps, one above another, any reflex echo of the sound can at all become perceptible. I deny the possibility of it. The sound in such a building never encounters at the same instant of time a resisting mass from which a reflection, sufficient to be perceptible to the hearing, could be possible. It strikes the first range of seats before the second, and the reflex echo from the first is lost ere that from the second has arisen, and so on up to the top. The ancients, inasmuch as all their theatres had this arrangement, cannot have depended at all upon the reflex echo of sound." †

It may not unnaturally occur to any one wishing to obviate the difficulty of hearing, and seeing too, which occurs wherever the floor on which the audience is placed is level, and the speaker is only a little raised above them, that by placing him on a sufficiently high elevation every one would be able to look and listen tolerably clear of his neighbour's head. And, in point of fact, this plan was very extensively followed in churches built in the last century, where the pulpits are of great height. It does not, however, often answer well; and one of the reasons is to be found in the fact, that both speakers and singers throw their voices nearly straight forward. It is far more natural to speak or sing upwards than *downwards*, and if any effort of voice has to be made the very action of throwing back the chest and head, which will send the voice *up*, seems needful to give play to the lungs. And further, of the sounds thus thrown *downwards*, almost every particle not heard would be absorbed by clothing, benches, cushions, and so forth, which would prevent the upper part of the building being properly filled by the sound. If the speaker is to be placed high, he should be very high—near the ceiling, or under a very large sounding-board. Those who have frequented the oratorios in Rome during Lent may remember that the orchestra is high up—almost close to the ceiling—and the sound seems to flood down upon the auditory in a fine way, reflected downwards by the ceiling, as well as radiated downwards from the instruments. Under ordinary circumstances, however, those who have most experience advise that the floor of a pulpit or that of the front of an orchestra shall be kept quite low; and Chladni,* after instancing some examples to prove that this is in practice found to be the proper position for an orchestra or speaker, adduces as a reason that the lower strata of air being much more dense than the upper in a crowded room, any sonorous undulations excited there will much more readily spread among those strata, and be communicated by them to the upper and lighter parts of the atmosphere, than would be the case if undulations excited in the lighter air had to be propagated downwards. In over-heated rooms this consideration becomes a very prominent one.

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* "Akustik," p. 37.

† Consult Chladni, *traite*, sec. 208.

An obstruction to the free passage of sound is presented by every adverse current of air and every variation in the quality of the atmosphere or its temperature, by every sudden contraction of the space through which sound has to travel, and by some, if not by all sudden enlargements of space.

The necessity for providing for the complete ventilation of all public rooms rests happily on the demands of an imperious necessity, apart from the collateral benefits which may be rendered to the acoustic qualities of the apartment; still it deserves to be remembered that an ill-ventilated room is likely to prove bad to hear in. It ought to be borne in mind too, that even a very gentle current exercises a strong influence upon the course of sound, favouring or opposing its progress, as the case may be; and that consequently, in arranging for ventilation, it will be best to avoid creating a current that shall set in from the audience towards the speaker, or even one that shall pass across the space between them, but that it will be of advantage to direct the ventilation so that whatever movement takes place in the air shall follow the same direction as that towards which the speaker throws his voice. This has been aimed at in the Surrey Gardens Music Hall.

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* *Allgemeine Musikalische Zeitung*, 30th August, 1826.

There is a difficulty in hearing well in those parts of a room where the sound would have to enter an opening, or a space that is restricted in comparison with the parts adjoining; this is a matter of common experience, and it is in consequence of this that persons placed under a deep gallery can so seldom hear satisfactorily.

It probably will not often occur to architects to have to encounter the obstruction that occurs when sound passes from a very confined space to a free and open one, but it is well to know that such an obstruction really exists, and that in the case of a railway tunnel, or similar tube with ends communicating with the open air, it is powerful enough actually to occasion an echo from the mouth of the tunnel, distinctly audible to those within it.*

Lastly, it is right to observe that sometimes features in a building which act to a limited extent as obstructions are yet very properly introduced because advantages attend their use which cannot be secured otherwise. The best instance of this is the introduction of columns into the interior of churches, which as we shall find when we come to treat of church arrangements, although they themselves do to a limited extent interrupt sight and sound, yet are necessary to the employment of other structural features, found by experience to be very conducive to good hearing.

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* Chladni (*Traité*, sec. 205) and Boit. *Mém. de la Société d'Arcueil*, tom. 2, p. 403.

4. *Reverberation.*—This term we shall employ to designate those effects of excessive resonance or of indistinct and incomplete echo which, though not amounting to a distinctly audible echo, confuse sounds—effects that are unpleasantly familiar to most persons, and are the more formidable because the agents that cause them are less obvious than those which act either by absorption, obstruction, or echo. Reverberation is sometimes due to defects in the proportions or form of a building, sometimes to the materials employed, sometimes to the conduction of sound along the walls, and at other times to the spaces above the ceiling, below the floor, or beyond the walls of a room. It is distinct from echo, properly so called, notwithstanding that at times an echo much broken or frequently repeated is the cause of this interference, or one so similar as to pass by the same name, but in nearly all cases it may be described as an overdose of resonance. This being the case, the discussion of the subject may be postponed to a great extent till the next division (that on auxiliaries), which includes resonance among its subjects, although a few general observations will be in place here.

Apartments of bad proportion, and especially such as are disproportionately lofty, and have plain unbroken walls, seem very subject to reverberation, and vaulted ceilings or large open skylights where they exist in such rooms, appear also conducive to the same defect. In empty houses a great reverberation is perceptible, which diminishes as the floors are covered with carpets, and the rooms filled with furniture. In short, empty spaces, especially towards the upper part of an apartment or communicating with it, are liable to be unduly sonorous, and it is probable that cutting them off by even a very slight interruption would improve the hearing in most noisy rooms.

It is desirable that the architect should be aware that the dampness of walls conduces to a very considerable extent to reverberation in a room. Dr. Hutton gives several illustrations of this fact;* and it will often be found that a building hastily completed (especially if its walls be plastered internally), and at once occupied for public purposes, will for some months fail to give satisfaction to the extent that has been hoped, although ultimately, as the walls lose their moisture, acoustic defects will disappear. The cause of this phenomena is obscure, and no satisfactory explanation has hitherto been brought forward, but the phenomena itself is none the less a matter of common observation; and in a new building it may often be as well to hang up a little drapery for a few months, which can be safely taken down when all gets quite dry.

In the avoidance of actual reverberation, notwithstanding a near approach to producing it, will lie the great skill of an architect, or, in other words, the greater the amount of genuine resonance he can introduce into his building the more agreeable will be the effect it will have upon the human voice, and musical instruments of all descriptions.

Some difference most probably exists between the nature of that disturbance produced by incomplete echo, or by small sonorous cavities, and that produced by the excessive sonority of a large body of air; for there are cases of extreme resonance, where an unfavourable influence is exercised upon sound, while yet no trace of echo is perceptible at all, and the interference with sound is so much more musical than noisy, that it hardly can be included under the term reverberation as commonly understood. But the distinction is a nice one, and as separate terms do not exist, the word reverberation must be held to comprehend both smothered echo and excessive resonance.

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* Mathematical Dictionary.

"The coffers," observes Lachez,* "with which ceilings are decorated, vaults, ornamental niches, the reveals of doors, and other similar recesses, all afford little cubes of air which vibrate each one with its own appropriate vibrations, like a kind of organ-pipe, under the excitement of the undulations in the building, and add to the fatiguing resonance of halls by augmenting the sum of confused noises."

In rooms where purity of tone and ease of speaking are of importance, with a view to avoid the evil indicated in the above extract, an evil the reality of which is seldom recognised to the extent its importance demands, the adoption of splayed reveals to window and door openings will ordinarily be found advantageous; if square, these reveals should not in such rooms be deep; and deep coffers in the ceiling or open square skylights, should be dispensed with. Closing up recesses in side walls by means of shutters or an inner glazed sash, and substituting plain ceilings for coffered ones (as was done with success in Exeter Hall), and fixing a horizontal frame filled with glass, or even with light canvas below the opening of a square skylight, will often effect an improvement in rooms where the features that have just been pointed out as injurious exist, and are found to exercise a prejudicial influence.

Under some exceptional circumstances, it is desirable to encourage reverberation—at least, it is no disadvantage for it to exist in public places of mercantile resort. If this be the object, almost any ordinary corn exchange would furnish a good model to follow, for these buildings are nearly all famous as being bad for public speaking; they usually have smooth, unbroken, and lofty plastered walls and plastered ceilings, are lighted from skylights, and are of somewhat square plan and lofty proportions.

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* Optique et Acoustique, p. 311.

In this instance, as in many others, the hardness of the surface presented by the walls seems to help to render the rooms noisy, and this is always likely to recur where hard, smooth linings are employed. It is fair to admit that the opinions of some of the writers to whom repeated reference has been made have been very decidedly expressed in favour of the employment of hard substances for the material, and smooth plaster for the lining of the walls that are to contain an auditory. Lachez* and Rhode† agree in this view, in which, nevertheless, it appears impossible to concur with them. Were it only desirable to obtain the greatest amount of sound possible, or, in other words, the loudest noise, regardless of quality or distinctness, we no doubt ought always to employ the most perfect of reflectors, just as we line such a room as a French *café*, which we wish to render dazzlingly brilliant, with mirrors; if, however, we desire purity of tone, it will be better to seek it in the musical tremor of wooden linings than in the conduction and rattling reverberation of hard polished surfaces, just as with the same aim as regards light we should in rooms where quiet brightness is desired replace the mirrors by bright but lustreless linings of paint or paper, or by light coloured draperies. This subject it will, however, be necessary to resume when we come to investigate resonance, while the principle now laid down will be found to be borne out practically in many of the instances that will be adduced of buildings good for sound.

Echo.—Echo is one of the simplest and best understood phenomena of sound. The interferences of echo with primary sounds are easily recognised, the causes of echo are readily detected, and the ordinary forms of echo are more completely reducible to laws, and more capable of being accurately provided against, than those of any other interference with distinct hearing whatever.

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* Optique et Acoustique, pp. 10 and 35.

† Theorie der Verbreitung, &c., pp. 61, 62.

Sound, when it meets with an obstacle of any extent opposing a tolerably flat surface to its course, will be reflected; this is a matter of common experience, and the reflection or echo of *light* is so familiar to us from our constant use of artificial mirrors, that the analogous action of plane surfaces upon sound is recognised at once the moment it is pointed out. The general subject of reflection of sound, the law that governs that reflection, and the manner in which reflection merges into conduction have been already referred to.*

That particular description of reflected sound which commonly comes under the title of echo, is heard when the reflecting surface is at some considerable distance from both the speaker and hearer, for an echo is a reflected repetition of an original sound, heard sensibly *after* that sound. If the reflector be very near the auditor, or very near the speaker, it will be obvious that the reflected sound will fall on the ear almost at the same moment as the primary one, and in that case, although distinctness may be impaired, the peculiar interference that is caused by the echo of one syllable falling on the ear simultaneously with some subsequent syllable will not occur, and no separate sound will be perceptible.

To produce a defined echo then, the reflected sound in its passage from the speaker to the reflector and from the reflector to the hearer, must make a sensibly longer journey than the sound going direct from the speaker to the same hearer. In a large room of any ordinary shape this can hardly occur, except in consequence of reflection from a lofty ceiling, or of reflection from an end wall opposite the speaker and behind the hearer; in the first case, the path of the sound going up to the ceiling and coming down again follows the two sides of a triangle, of which the path of the direct sound will describe the base; in the second, the reflected sound travelling almost parallel to the original one passes the hearer, at the same time that the original sound reaches him, and has subsequently to make the journey to the end wall and back before it is heard as an echo. In either case the difference of length between the paths of the two sounds will furnish a measure of the time that will elapse between the two sounds as perceived by the auditor.

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* Ante, pp. 23, 29.

Of echo from a ceiling the reading-room of the British Museum furnishes an instance. In that room "when few are present, a very great repetition is observable. Standing in the centre, the echoes seem to come from the crown of the dome; if on one side, the echoes come from the opposite side."* It does not often happen that ceilings are sufficiently lofty, and so situated as to give rise to so distinct an echo, but when that is the case no remedy can be applied, except one that will cut off the reflecting surface from direct communication with the part below. The article from which we have just quoted, mentions a large room at Coblentz, 92 feet long, 40 feet broad, and 46 feet high, which it was found impossible to make use of as a public law court on account of sonorous disturbance. This room was vaulted, and hanging a sail cloth across at the level of the impost of the vault proved a complete cure, so that a linen covering, slightly painted, was permanently fixed in this situation, and made to do duty as a ceiling.

The lower the ceiling the less chance there will be of an echo from it, and if it be high it will be well to dispose it in some such form as will afford few or no reflecting surfaces so directed as to throw sound down upon the auditory.

The most satisfactory treatment for the wall which faces the speaker or musicians, and which is the usual cause of echo where that defect makes itself observable, is to throw it into a semi-circular sweep, as has been done in the Free Trade Hall at Manchester, this will go far to prevent serious disturbance from echo. A projecting gallery, columns, frequent openings, curtains, cloth doors, or deep recesses, or some similar means ought to be adopted at this end of any room for public purposes, so as to break up or do away with echoing surfaces as far as possible; and when an echo actually exists from this, the most dangerous wall of any building, the most inexpensive expedient will usually be found to be to hang draperies in front of the wall, such as shall deaden the sound ere it reaches the reflecting surface. The erection of a gallery running across the end of such a room, where none existed previously, has frequently been found to diminish and sometimes to destroy an echo. And it will often be found very serviceable in new buildings to form an end gallery, if it be only a small one, as it affords a better means than almost any other of breaking up this part of the room.

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* Architectural Publication, Society's Dictionary of Architecture, part 10, A.D. 1860, art. Echo, p. 10.

A remarkably shrill and unpleasing echo can often be detected by a person standing in one corner of a room with square angles, if sounds are excited in the corner diagonally opposite; in this case the sound is apparently twice reflected, and two of these doubly-reflected echoes are heard at once. The probable path being represented in the accompanying diagram (fig. 11), where S is the speaker, and H the hearer.

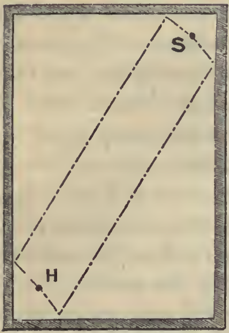

Fig. 11.

In rooms of this class, when they are long, a very unpleasant shrill echo will be often audible near the two remote corners, and in some cases near all four corners, even if the speaker be placed centrally; this is due to the reflection of the *conducted* portion of the sound.

In these rooms, as the dotted lines on the diagram (fig. 12) will show, a portion of the sound will be conducted along the back wall and each side wall, and in either case will meet a reflecting surface at right angles, which will return it again along the same wall, to the very serious discomfort of those who occupy those corners of the room. A similar echo is apt to occur where a ceiling joins a wall at right angles. The obvious method of avoiding these defects—defects which are perceptible in many rooms that are in other parts excellent for sound is to cut off the angles either by a cant or a curve, and to bring the ceiling down on to the walls by a cove or a sloping side. It will also be advantageous, and often convenient, to place entrance doors at the two angles furthest from the speaker, or in some similar way to break up the plane surface in that neighbourhood.

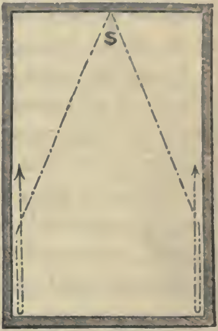

Fig. 12.

Among echoes that have become famous, some are remarkable for the number of repetitions of a single sound that they afford, others for the length of time that elapses before they are heard, thus allowing many syllables to be uttered all which are faithfully returned, and others for the transposition or other alteration that the repeated sound has undergone before it is sent back, but no practical purpose could be served by introducing the descriptions of them, which are to be found in most works on acoustics.*

The echoes that repeatedly return sounds will all be found to be produced by a combination of two or more reflecting surfaces, in such positions relatively to one another that the sound travels to and fro between them till its strength is exhausted; the hearer in such a case must of course occupy a position in the path thus traversed. Perhaps the most celebrated of this class is the one at the Villa Simonetta, near Milan. The echoes that repeat many syllables do so, of course, only because the reflecting surface is remote from the point from which persons speak, and all other circumstances are favourable to the preservation of the force of the sound during so long a journey.

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* See the works of Dr. Hutton, Herschel, Brewer, &c., and the Dictionary of the Architectural Publication Society.

A very few cases are described as existing of echoes, which instead of repeating the original sound return some harmonic of that sound. To this phenomenon, of which a striking example is said to exist on the Lakes of Killarney, Dr. Brewer * gives the name of the harmonic echo, and it must be admitted that its cause cannot at present be explained, nor would it be possible in the absence of careful observations and experiments to offer more than a perhaps valueless conjecture as to the real nature of so remarkable and elegant a phenomenon. A satisfactory and self-evident explanation of the reasons why an echo of this character should ever occur, and a description of the combination of circumstances necessary to produce it, will however, when it can be furnished, be of value to architectural acoustics, as tending to throw light on that important and obscure subject, the voice or note proper to individual rooms.

Bad proportion and bad shape have not been separately enumerated among obstacles to the diffusion of sound in buildings, not because they are inactive, but because the influence they exert ordinarily takes the form of one or other of the interferences already examined in detail.

Bad proportion, for example, is apt to lead to reverberation, and consequently to indistinctness. Ill disposed forms generally may produce both this and all the other varieties of obstacle enumerated, or a combination of several of them; and, on the other hand, the securing a good proportion and a suitable disposition for an interior sums up the whole secret of success, so far as the *form* of the building apart from any consideration of its materials will secure it. At the same time, however, it will perhaps be right that attention should be directed to unshapeliness, as possibly the cause of failures which cannot quite be attributed to any influence that has yet been described. In considering good proportion as an auxiliary, it will be found that the existence of certain and simple numerical ratios between the main dimensions of a room may be expected, as has actually occurred in instances, such for example as Donaldson's rooms,* to lead to a remarkable excellence in the quality of sounds produced there. The absence of this proportion will necessarily be attended by the loss of this advantage; but is it not possible that the existence of very inharmonious proportions may exercise an influence on sound, as disadvantageous as that of the approved proportions is good? The cause in both cases would be of the same nature, and an attempt will be made in the succeeding section to indicate the direction in which it is to be sought for.

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* Brewer on Sound, sec. 474, 479.

III. Buildings can afford *auxiliaries* to the propagation of sound.

The form, materials, proportions, dimensions, and contents of buildings are capable of exercising a favourable influence upon the transmission of sound, acting partly by preserving the undulations from dispersion and decay; partly by impressing an initial direction upon them, or by promoting their progress when that direction is established, and partly by reinforcing or strengthening them. This last description of assistance, viz. that which acts favourably upon sounds by reinforcing or strengthening them, is derivable from resonance, the other two from reflection and conduction.

We shall first therefore pass in review the three agencies of resonant bodies, of reflectors, and of conductors successively; and although it is to a happy combination in which each of them shall contribute its share to the total result that we must look for perfect success, yet it will be well to form a distinct idea of the operation of each separately. It is almost needless to repeat that it will be assumed throughout, while treating of auxiliaries, that the obstacles considered in the first division of this chapter, have been to a great extent if not entirely avoided or removed, so that free scope for the uninterrupted radiation of so much sound as would directly reach the hearers has been secured.

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* Described in the succeeding section.

Three very familiar instruments in common use will supply us with examples of the three modes of action about to be considered and will furnish admirable standards for reference. These are the violin, the speaking-trumpet, and the reflector. Each of these instruments depends for its power over sound upon one principle only, and there is no influence capable of being advantageously exercised over sound (unless possibly the influence of proportion proves to be an exception), that cannot be directly referred to a mode of action analogous to that of one or other of these. The action of the violin is an example of pure resonance; that of the speaking-trumpet of pure conduction; and that of the reflector, as its name imports, of pure reflection.

It is to the form of a building that we have to look for the favourable direction it may impress upon sounds, or maintain in them, in other words, for advantageous reflection or conduction; it is to the materials, and sometimes to the included mass of air, that we must look for such resonance as shall be advantageous. Let us examine then, first, the assistance that the *form* of the building may afford to the diffusion of sound, commencing with *favourable reflection.*

The laws governing the reflection of sound,* together with the circumstances under which that reflection causes disturbance by echo,* being borne in mind, it will need no proof that favourable reflections cannot be expected from the walls or surfaces behind the auditors, or from any surfaces remote alike from auditors and speakers. It is never possible for a reflected sound to reach the auditors exactly at the same instant as the original one, and consequently there is a risk with all reflectors of impairing *distinctness;* a risk, however, which it is often prudent to encounter rather than to forego the great addition to the loudness of sound that accrues from the employment of a well placed reflecting surface. This indistinctness seems to become more apparent the more hard and polished the reflector is, and it is consequently common to find that, if a speaker is placed in front of a large mass of wall with a hard plastered surface, the effect upon his voice will not be altogether a pleasing one, a sharp ringing echo will occur, too close after the original sound to be distinguished from it, but too defined and distinct to blend with it, and very apt, consequently, to produce confusion.

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* Ante, pp. 23, 29.

Such reflectors, then, as are likely to prove beneficial must be suitably directed surfaces in the neighbourhood of the place where the sound that is to be assisted originates, and will be more valuable auxiliaries if of resonant material than otherwise; among them are to be included screens and sounding boards of various descriptions, and also for the most part portions of the walls and ceiling of the building.

The parabola has been always a favourite form for such surfaces with those who have paid more attention to the theory of sound than to practical experience, on account of the faculty it possesses of reflecting as parallel all rays which proceeding from its focus fall on any part of its inner surface.

Chladni even gives it as his opinion that "when it is wished that an orator, or a singer, or an instrument shall be distinctly heard, a parabolic form of the walls and ceiling would be very suitable; the two branches of the parabola could be made to pass into parallel straight lines; the sound should be produced exactly in the focus of the parabola, and all that did not directly arrive at the auditors would reach them in directions parallel to the axis." * These views have been shared by many other writers, and a concave parabolic reflector, with the speaker in its focus, has been considered as a safe and certain means of augmenting the intensity of the voice. Happily the experiment has been pretty fully tried, and such results as are accessible seem to prove that, though without doubt a great augmentation of the sound is procurable, yet the concomitant disadvantages are so grave as usually to outweigh the benefits of such a reflector.

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* Ante, p. 54.

For accounts of this experiment we must have recourse to a pamphlet, published in London in 1829, giving a description of a parabolic sounding-board erected by a clergyman, the Rev. John Blackburn, in his church at Attercliff, near Sheffield. The account is well written, clear, and precise, and may be supplemented by an abstract of a paper communicated by the same author to the Society of Arts, which, together with correspondence, is preserved in the "Transactions" of the Society.† From these sources, together with information very carefully collected on the spot, and communicated by Mr. Holland, of Sheffield, we gather that the church at Attercliff was newly built at that time. The area of the interior is a rectangular parallelogram, 95 feet by 72, with an elliptical recess at the east end, 10 feet deep and 32 wide; the roof is described as "vaulted and groined," and the highest point of ceiling of nave is about 56 feet from the floor; there does not appear to be a clear-story in the church, but there are galleries at the sides and west end.

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* Acoustique, parag. 210; consult also Allgemeine Musikalische-Zeitung, August, 1836.

† Vol. xlviii. for 1830-31.

On attempting to make use of the newly-built church, the resonance was found powerful, but the sound so indistinct and confused that no exertions on the part of the speaker could make him audible. The first expedient tried was to change the position of the pulpit, the floor of which is 9 feet above the level of the church floor. It was tried in various situations, and the least bad was found to be in the middle aisle, and 15 feet in front of the altar rails; but still the evil was not cured. An ordinary flat sounding-board was then tried, and proved beneficial to those seats just about the pulpit, where it was least needed; "but its general effect," says Mr. Blackburn, "was so decidedly disadvantageous that it was again taken down."

"The desired object was to convey a distinct sound to remote parts of the church; under the impression that this might be attained by intercepting so much of the sound as escaped behind and echoed in this part of the vaulted roof, as also by giving it a right direction, and conceiving that a parabolic figure might be so applied as to answer these ends; the author of the pamphlet made the trial, and the issue has more than realised his hopes and expectations."

It is further stated that after the reflector had been fixed, persons in the end galleries "were able to hear even better than those near the pulpit, but at the sides;" and in fact the difficulties of speaking and hearing were felt to be entirely removed.

The reflector was constructed very carefully of pine wood, and was fixed with its axis inclined forward to the plane of floor, at an angle of about 10 or 15 degrees, and elevated so that the speaker's mouth might be in the focus; its dimensions, as given in the pamphlet, were as follows:—

The distance from the focus to the vertex = 2 feet.
The length of abscissa = 4 feet.
The length of co-ordinate to axis = $\sqrt{32}$ feet.
= nearly 5·7.
= radius of outer circle.

The paper read before the Society of Arts was accompanied by a model, now in the Natural Philosophy collection of models at London University College, and from inspecting this and some cuts in the pamphlet, one can gather that the reflector must have appeared a great incumbrance to the pulpit, a defect which perhaps, however, could be in part obviated, were there no other obstacle to the employployment of this instrument.

The publicity given to this successful experiment, an outline of which was also communicated to the Royal Society, induced a repetition of it in other churches, one of the first attempts being made at Cambridge by the late Professor Farish, who subsequently wrote to the secretary of the Society of Arts, saying that there was no part of his church in which the sound was not louder than before the sounding board was put up, but that the greatest improvement was gained by that part of the audience who were at the greatest distance, so much so that the remote end of the church had become the most favourable for hearing. In at least thirty instances was this expedient tried, including one new church at Darnall, also near Sheffield, where the end of the building was built in a parabolic shape, and the pulpit fixed in the focus. Among the number may be mentioned, besides the reflector at Cambridge, two erected at Oxford; one at Trinity Church, Huddersfield; one at St. Sepulchre's, Smithfield; one at St. Philip's Church, Sheffield; and the last known to have been erected some seven or eight years ago at Duckenfield, near Manchester. A reflector of a similar character is or was fixed behind the pulpit in Trinity Church at Margate.

As the reflector came to be more extensively tried, it was far from being so universally liked as its success at first seemed to render probable, and both the original one at Attercliff, and many of those subsequently erected have been since pulled down; the great objections to their use being that the speaker heard the echo of his own voice dinned into his ears in a bewildering manner, while he was also liable to be molested by hearing the little sounds produced among the auditory down to the whispers of the occupants of the furthest part of the church, collected as in a great ear and intensified till the slightest of them were audible. This annoyance was to some clergymen so intolerable that they found it impossible to occupy pulpits fitted with the reflector.

Further, the benefit of the apparatus could only be derived by those who were able to keep themselves from moving about, as any remoteness of the mouth from the centre of the reflector, caused a corresponding diminution in the volume of reflected sound; and lastly, experience proved that the result obtained at Cambridge, namely that all parts of the church were benefited by the reflector, did not follow its introduction in all cases, for in one instance,* one of these reflectors after being in use a short time had to be removed, because though it assisted those directly in front of the speaker, it robbed those at the sides, showing that probably the apparatus will be much more serviceable in a long narrow building than in a wide one. It is not impossible that in the Attercliff church, where it was originally introduced, and at the time found indispensable, the need for assistance to the voice may have been greatly diminished by the walls and plastering becoming perfectly dry, but it has not been possible to ascertain whether this is the case.

The experiment in its general results seems to show that, while a powerful means of throwing forward the voice in one direction is unquestionably within our reach wherever these reflectors can be applied, the number of instances in which they will be available cannot be expected to be great; and further, that such a feature as a parabolic reflector can never without danger be introduced as part of the structure of a building, but ought always, where employed, to be a piece of furniture only, and one capable of speedy removal when necessary.

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* St. Philip's Church, Sheffield.

An ingenious application of the reflector has been lately made with very happy results by Mr. Penrose, in St. Paul's Cathedral, where, as is well known, a temporary pulpit has been erected, and a multitude of seats placed in the central part of the church under the dome, for the accomodation of the great congregations that have attended special services there, of which services sermons formed an important part.

It was soon found that the echo from the dome interfered with the comfort of both preachers and hearers, and that an expedient for correcting this defect was necessary. Accordingly a reflector of organ-pipe metal, 10 feet in diameter, was fixed over the pulpit in a horizontal position, the section of which was hyperbolic, and with the convex side turned downwards.*

The effect hoped for was that first the direct sound going up into the dome would be cut off, and then that some portion of it would be thrown laterally over the congregation, and these objects appear to have been quite attained. A remarkable result attributed by the architect to this reflector, is that at a small elevation above the floor, for example in one of the side galleries, the preacher is not nearly so well heard as he is by persons standing at the same distance and among the crowd, notwithstanding the advantage of an undisturbed and direct line of communication above the heads of all the congregation.†

It will be observed that this application of a flat curve to the purposes of a sounding board is free from the objections justly urged against the parabolic reflector of Mr.

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* A familiar illustration of this unusual arrangement may be obtained by supposing for an instant that the pulpit is represented by a common wine glass, and holding over it at a few inches distant a watch glass with the hollow upwards. The watch glass will then represent the reflector.

† See Transactions of Royal Institute of British Architects, session 1860-61 ; Discussion on Paper on Acoustics. Session 1858-59, paper on St. Paul's Cathedral.

Blackburn; it will not cut off the sound from persons behind or at the side of the pulpit, not a vibration of the sound that reaches it will ever be again returned from it to the preacher, and if it be at all large it does not impose any necessity of standing constantly in exactly the same part of the pulpit. These considerations make it worth attention as a form that might frequently be substituted with advantage for the flat form of sounding board in common use in churches. At the same time it must be borne in mind that, while the action of a sounding board like this is uniform, it must also of necessity be feeble in comparison with that exercised in one given direction by a concave reflector on the plan of Mr. Blackburn.

The parabolic reflector has been, at least in one remarkable instance, employed to prevent the transmission of sound. This was done in the United States, in the Berks county prison, and some account of the arrangement is to be found in "The Builder."* It appears that in this prison, which is constructed on the cellular system, now commonly adopted in this country, it was desired to prevent the possibility of communication between the occupants of adjoining cells, which even if the walls would transmit no sound, had been known to take place through the air-flues belonging to the ventilating apparatus. There were two such flues in each cell, one connected with the inlet and the other with the outlet air channel, and the account states that "two enlargements are made in the flues 10 feet apart," meaning probably two in each flue, and that in each of them is fixed a reflecting surface made of earthenware, and in the form of a paraboloid. The direction in which the axis of the reflector was fixed is not specified, probably it was parallel to the sides of the tube, and the concavity of the reflector was directed towards the end of the tube from which the sound would come.

The result was the perfect isolation of the cells in respect of sound, it being quite impossible to hear the loudest shouting at all from one cell to another. The cost of these reflectors was it is said extremely small.

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* For 1847—p. 618.

Under ordinary circumstances, a straight reflector will be found more advantageous than any other, principally, no doubt, on account of its action being pretty uniform, though only moderate, and it will act better above the speaker, and at a slight inclination, say from 20° to 30°, than if it be behind him, and either perpendicular or inclined, or above him and horizontal. It will, however, even if horizontal, be of some use, especially if it projects some way forward in front of the position of the speaker. The sounding boards commonly fixed over pulpits, both in our own places of worship and in continental churches, are undoubtedly very advantageous, and often almost indispensable, and they are mostly horizontal.

The material of which a reflector is composed is probably an element of great weight in determining the amount of benefit derivable from it. In the Surrey Music Hall a large reflector was fixed, inclining a little upwards, but not at a great angle, and went over the entire orchestra. This it is believed was very conducive to the success of that building, and it was especially required that it should be constructed not only of wood, but entirely of old materials, dry and thoroughly seasoned.

From what has just been said, it will therefore be seen that a double advantage is procurable; by bringing down the ceiling over a speaker's head and contracting the walls on each side of him, not only is a great deal of space saved, but surfaces are ordinarily obtained, the reflecting action of which is likely to prove favourable. In all arrangements of this kind it is well to bear in mind that surfaces must not be so placed that they will throw the sound on to some second surface behind or above auditors, from which it will be reflected down among them; should this be allowed to occur, an echo, or some disturbance approaching to it, will be audible. In most ordinary large rooms, as was shown at p. 56, a disturbance of this nature is audible, should sound be excited in one of the angles of the room, to those auditors seated in the angle diagonally opposite.

We may now turn to direction and conduction of sound, a subject closely allied to reflection, and of which the speaking-trumpet furnishes us our illustration.

A conduction or direction of sound, such as shall in connection with favourable reflection, prove an auxiliary to hearing in buildings, implies that a portion of the sound which might have passed off without advantage to the hearers is thrown forward into a useful line, that the sound whether reflected or directly radiated has free scope to travel where it is wanted to go, and that the shape of the building is such as not only to admit of its reaching certain points, but in a sense to guide it towards them.

It is difficult, perhaps, too, unnecessary, to lay down any rules for the conduction of sound, and we shall have to remain satisfied with a few general principles, the application of which to individual cases must be left a good deal to the discretion of the architect at the time.

At page 26, the conduction of sound to great distances, where its lateral decay was prevented, came under notice, and it is very much to this cause that the power of the speaking-trumpet is due. This instrument was long thought to act by reflecting the sound from side to side; but this theory, now known to be inconsistent with the laws that govern the reflection of sound, was practically shown by the experiments of M. Hassenfratz, so far back as 1804, not to be in accordance with observed phenomena. That philosopher presented a paper to the Institute of France, which has been quoted by most subsequent writers as detailing the best, perhaps the only decisive, series of experiments on the action of this instrument.*

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* An abstract is to be found in the Journal de Physique, vol. lix. for 1804 (not vol. lvi., as erroneously stated by Chladni, and copied from his work by five or six writers). The original paper appears to have been printed in "Le Recueil des Savans Etrangers."

It was found in the course of these experiments that while variations in form of the speaking trumpet affected its power, the material of which it was made might be altered without any change in the sound heard; so that a speaking-trumpet of polished brass and one of paper, or one lined with cloth, would, if of good shape, be equally useful. The conclusion come to by M. Hassenfratz was, that the air contained in the interior capacity of the instrument being enclosed by its walls, is compressed by the impulses of the sonorous body in a more vigorous manner than would be the case if the walls had no existence; each individual particle consequently contracts a greater amplitude of vibration in that direction in which it is free to move, and is capable of transmitting that action to a greater distance before it is entirely lost.

Of all forms there seems little reason to doubt that the form of a speaking-trumpet is the most appropriate for conducting sound onwards with undiminished force, and in fact the action of a speaking-trumpet seems almost to intensify the original sound, so completely does it collect the whole of it, and impress an onward direction on it. A room like a large speaking-trumpet would be too unsightly an object for it to be practicable to carry it out literally, but one with divergent walls near the speaker, and a rising ceiling over him, will be enough like a speaking-trumpet, with a straight sided tube beyond it, to favour transmission of sound. In divergent walls and an ascending roof there is, too, another advantage, because by them the space behind and above the speaker is contracted, as has been already explained to be desirable.

This arrangement, when it imparts to the sound a strongly marked direction, will, as in the case with the speaking-trumpet, send it on in that direction almost exclusively, and a very moderate amount of lateral confinement, coinciding with this initial direction, whether that initial direction be produced as now described, or imparted by a reflector, or merely due to the natural degree of forward impulse communicated by every speaker to his words, will prolong the range within which it remains audible to a great extent.

If these views are correct, it seems to follow that when the limits of direct radiation of sound are exceeded, the speaker should be placed near one extremity of the building, and the arrangement of the room should be made subservient to the double aim of first imparting to sound an initial direction, and then conducting it forward in that direction. So that any very large building, to be acoustically good, ought to have one dimension decidedly predominating over the others, and that dimension usually its length, for *you cannot greatly extend a building in every sense without its soon becoming so vast that a voice will be lost in it, but you may with safety extend it very greatly in that direction in which the voice is travelling*; it will further follow that there should be as little breaking up of the volume of sound as practicable, as few pocket holes for it to be lost in, or projections for it to be broken up against as possible; and further, there should be unquestionably good proportion in the entire structure.

It must be borne in mind that the form of the apartment, when it is spacious, seems to exercise a great influence upon the progress of sound, and that wherever the sound is wanted to get to, there should a way be made straight and uninterrupted: also that as few opportunities as possible for its escape on its way should present themselves, for every such opportunity will be sure to draw off a portion of the force; and lastly, that a great stream of sound is more audible than a little current, even at the same distance from the source.

It does not, however, follow from all this that there is no danger from perfectly smooth unbroken walls and ceiling; we have already seen that they are liable to foster reverberation, and it is therefore probably always safer, *to a moderate extent*, to break up the surfaces, and to break up the voids also, as is done by the introduction of columns, roof timbers, and similar features. This is especially desirable in those parts of the internal surfaces of the building upon which the rays of sound fall at a very flat angle. The conducted wave* that will roll along the walls and ceiling in such parts, is not in itself of good quality, and is peculiarly liable to pernicious reflection †; it is better therefore that it should be dissipated by the unevenness of the surface, along which it would otherwise travel. An illustration of a mode of doing this will be found in the arrangement of the Free Trade Hall at Manchester, of which building plans and a description will be given further on.

Perhaps the Floral Hall in Covent Garden may be safely referred to as bearing out part of that which has been just said. This building, which is framed in iron and roofed with glass, has a very long nave and two short transepts, and over the space where they cross a dome. Concerts have lately been given there, the musicians being under the dome; and, as might have been expected, the dome and the transepts seemed to swallow up much of the sound, to destroy its volume, and very remarkably to impair its tone; but there was a great deal of sound thrown forwards into the nave, and as it advanced the influence of the building upon it appeared to increase, so that the music was decidedly better heard at the extremity of the nave than it was half way down, notwithstanding that the distance from the orchestra was much greater. In this instance the effect of the roof and sides in conducting forwards that portion of sound which came into the nave was very evident.

In determining the form of an interior, an analogy, somewhat fanciful perhaps, but possibly suggestive, may be found between a building and a ship. It may be presumed that the motions of sound will travel pleasantly and undisturbedly past such forms as would belong to the interior of a vessel, which itself would move most easily in a fluid. Certain it is that a resemblance does exist between the roofs of some of our most celebrated acoustic buildings, and the inverted hull of some large ship, and if there is no possibility of exactly defining the reasons why ceilings of this form should be advantageous, experience at any rate is in favour of them.

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* Ante, page 29.

† Ante, page 57.

If, however, the ceiling is to be flat, we have already shown that it ought not to meet the wall at right angles. A flat ceiling with canted sides seems to have the advantage of reflecting down onto the auditory sound that would otherwise be either lost to them entirely, or else would only arrive after a double reflection, first from the sides of the ceiling to the side walls, and then from those walls down to the hearers. Of course a flat ceiling with coved sides, or one of oval or elliptical section, has to a degree the same effect. The ellipse was formerly much recommended for the form of ceilings; and Gibbs, a man of experience in his day, describing St. Martin's church, which he built, observes —"The ceiling of the church is elliptical, which I find by experience much better for the voice than the semicircular, though not so beautiful." This form was repeatedly employed by Wren, and was formerly not unusual for rooms and public buildings, and many of those so ceiled have undoubtedly proved advantageous for public speaking; where fairly admissible, therefore, it may be looked on as certainly safe, and ordinarily advantageous.

✓ We come now to the consideration of resonance, as the third and last of those auxiliaries to sound which have already been enumerated.*

Resonance in a building may be described as that quality which alters, intensifies, or prolongs sounds produced there, in the manner briefly described in the first chapter,† and arises from vibrations excited by the sound itself, either in the materials of the building, or in the air enclosed by its walls and roof. In excess resonance merges into one sort of reverberation, and long before that point is reached diminishes the distinctness of whatever is spoken, even while improving the quality of the tone; hence it arises that a difference exists between the degree of resonance safely admissible, in different buildings, which will be more or less as the building is to be used for speaking only, for music only, or for both.

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* Ante, p. 60. † Ante, pp. 29, 30.

It will be recollected that when this subject was first mentioned,* the violin was indicated as a musical instrument which depended upon resonance for its peculiar powers, and which might be with advantage kept in view, as furnishing a means of investigating, by analogy, the action of this principle.

It has been already remarked that the violin and instruments of the class which consists of a resonant body and a series of musical strings brought into very intimate relation, depend for all the beauty, and nearly all the power of their notes, upon the sympathetic vibrations roused in the reinforcing body by the strings when the latter are set in motion. M. Savart has in his lectures given a most interesting analysis of the nature and duties of every portion of a violin, and has also, in a paper on the subject, unfolded the results of many experiments.† Want of space prohibits any attempt to give even a condensed account of his researches, but a portion of their results it seems essential to introduce.

It appears, then, that the musical qualities of the violin result from the combined actions of all the separate parts of the instrument harmonised with wonderful success by many concurring conditions and expedients. The resonance of the upper and lower tables, that of the sides, and that of the included mass of air, are all employed in, and essential to, the bringing out the tone of the instrument in its perfection.

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* Ante, p. 60.

† L'Institut, Nos. 319, 321, 323, 327, 1840. Annales de Chimie, tom. 12.

Perhaps no work of human skill is more really surprising when scientifically examined than a good violin; no portion, even to the smallest, of the instrument can be altered, much less omitted, without deteriorating the quality of its sound; and yet there seems no reason to suppose that the perfection to which it has been carried is the result of anything except tentative experiments, and innumerable and gradual modifications. M. Savart has shown that while every portion of the instrument shares in or influences the vibrations it undergoes, the included volume of air is the one element which dominates over and harmonises the action of the whole. This in the best violins is of such dimensions and so circumstanced as to vibrate in unison with the key note in which they are intended to be tuned, namely, either the C, giving 512 vibrations in a second, or a note about a semitone more grave. Each one of the tables, when independent of this mass of air, has a sound of its own, and ought not to be in unison with the other or with the included air, but yet when all the parts are brought together the sound of the mass of air preponderating over that proper to the other elements, causes them to vibrate in unison with itself; at the same time, however, the presence of so large an amount of resonant wood imparts to the whole combination the faculty, which the mass of air would not have possessed by itself, of reciprocating any note which the strings emit.

This wonderful compound resonant body, having thus a note of its own, and that note in unison with the lowest that the strings fixed to it can give out, lends itself to the vibratory movements of those strings so completely as to sound in unison with every note they emit, however transient or however prolonged, and so conveys to the notes of a violin their peculiar tone, intensity, and loudness; for although the manipulation of the bow affords the artist on this instrument a range of expression and force almost infinite, it must always be borne in mind that were the bow and the strings only used with no resonant body* there would be neither power nor tone, and, in fact, no very great amount of sound at all.

Two elements seem here to be indicated to us, which must be considered both as separate and combined in their action on sound in buildings, namely, the resonance of materials, and the resonance of a mass of air; and the better to comprehend their importance, which seems to have received from previous writers less attention than it merits, it will be well to compare the influence which resonance exercises over sound in some simple instance with the influence of reflection or conduction.

Suppose, then, we take some small sounding body, such as a watch, a musical box, or a tuning-fork and, having first made it sound, when held in the hand in the open air, and noticed the distance to which it is audible, we then in succession place it in the mouthpiece of a speaking-trumpet, in the focus of a parabolic reflector and on a violin, or a table, or a pianoforte: we shall find that the three classes of instruments affect its sound very differently. The reflector and the trumpet will both cause the sound to be louder and audible to a greater distance, but only in one direction. The person at whom the trumpet is pointed, or towards whom the mirror faces, gets more sound, but a person at the side gets less; and where the quality of the sound could be accurately examined we should find that there was some deterioration in purity, and if the sound were articulate, or in some other way very sharp and well defined, some loss of distinctness would probably be very evident.

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* Ante, p. 30.

The effects produced on the primary sound by contact with a violin, a table, a pianoforte, or any other resonant body, are very different; it will be rendered perceptibly louder, but there will be an equal diffusion of it in the room, so that though it may not travel so far in one direction as either of the other instruments would send it, yet as far as it extends it will be equally heard in every direction (thus showing that *resonance is peculiarly adapted to aid natural diffusion*), and, further, will not only lose none of its distinctness, but it will gain in quality, so as to become richer and more musical than before.

This experiment may be taken to show pretty plainly that by employing the resonance *of elastic materials*, either alone (as in the table) or combined with a body of air (as in the violin), we have the means of strengthening, and at the same time improving the quality of sounds emitted under such circumstances as to command their support; and this is unquestionably more than can be said in reference to any agents that act by conduction or reflection. Let us now for a moment inquire into that less pliable influence exercised over sounds by a resonant body of air of determined magnitude, independent of the solid substances that cut it off from the surrounding atmosphere.

If we take as an instance the column of air in an organ-pipe, voiced to a certain note, and hold near the mouth of the pipe two or three tuning-forks in succession, of which one only will emit the note proper to the organ-pipe (or its octave or other harmonic), we shall observe that the sound of that fork will be very perceptibly intensified by the sympathetic vibrations of the air in the tube, while that of the other tuning-forks remains unaltered or nearly so;* thus illustrating the general truth already announced, that whenever a resonant body has a note peculiarly its own, its sympathetic vibrations afford a more energetic support to that note or its harmonics than to any other. This may be shown in a different manner by placing a tuning-fork in a state of vibration near the mouth of a flute, of which the keys and holes are so fingered that a person blowing the flute would produce the same note that the tuning-fork gives out; the column of air in the flute reinforcing the feeble note of the tuning-fork, a full clear sound will become audible. If the fingering of the flute be now altered to that suitable for a different note, the sound will be greatly decreased, though still some slight support may be afforded.

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* See Wheatstone's papers in "Quarterly Journal of Science, &c.," vol. iii.

These simple experiments demonstrate very clearly the inflexible nature of a mass of air, when so disposed as itself to emit a note, if uninfluenced by any contiguous body of a different character, and offer a strong contrast to the usual action of a plate of elastic, well-seasoned wood, which, it has been demonstrated, will vibrate in unison with any sound or sounds brought into connection with it,* as is shown, for instance, in the sounding-board of a pianoforte.

It appears then that, in the influence upon sounds of resonant bodies, we possess a means of altering their tone and intensifying them, and that this will be best done by bodies having the property of vibrating almost equally well in sympathy with any note, *i.e.*, not producing any very decided musical note of their own. The alteration in tone so produced is due to the *quality* of the new substance caused to vibrate, while the increase in volume and intensity results, the first from the greatly enlarged *bulk* of the vibrating body, and the other from its vibratory *energy;* for it has been satisfactorily shown by Savart, that these induced vibrations will sometimes possess an energy very much greater than the power originally brought to bear on the primary sounding substance could have produced, if applied directly to the resonant body.

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* Wheatstone in Journ. R. Inst., vol. ii. 1831. Ante, p. 32.

It will now become desirable to see if these principles cannot be shown to be applicable to buildings.

In all apartments, large or small, we have necessarily a body of air present, and we may, if we please, consider every room as a kind of gigantic organ-pipe,* the note of which can be excited in some cases by any noise of any sort, in others only by some one or more sounds bearing a certain relation to the pitch of its proper note, and if this note becomes audible, it commonly will be found that when once roused it will "ring," that is to say, will continue to speak after the original exciting sound has ceased. We may further, if we please, introduce resonant materials that will sound in unison with every note emitted near them, and will cease to sound the instant the original note ceases, and will change when a change takes place in its pitch. Let us consider each of these agents, taking the last mentioned first.

The employment of so pliable an auxiliary as the resonance of wooden linings, cannot fail in theory to commend itself for approval, and in practice will be found to have afforded great advantages where it has been introduced. The Surrey Gardens Music Hall, the Conservatoire at Paris, Her Majesty's Theatre, the Ancient Theatre at Parma, the lecture theatre at the Royal Institution, most of them buildings that will be again referred to, are all conspicuous for their excellent effect on sound, and are all constructed with a very large amount of resonant material.

Wooden ceilings, a wooden sounding-board, the lining of walls with wood, and the construction of internal fittings of wood, are all methods of advantageously introducing resonant materials. A building on columns, with long bearings for the floor, and a hollow space beneath, or one with vacant space above a wooden ceiling, are both likely to be much more resonant than if all were pretty closely filled up; and the same holds good of portions of buildings.

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* Lachéz, pp. 17, 18.

In the construction of an orchestra, for instance, various attempts have been made to render it such as shall vibrate throughout; and the common custom in Italy is to fix the orchestra of theatres over a species of hollow or trench, an arrangement which no doubt affords some little additional scope to the vibratory qualities of the wood of which it is built.

The ancients were acquainted with the advantages attending the use of wood in structures for public speaking. Till a very late period, the theatres of the Romans were all constructed of wood, and Vitruvius adduces this as a reason why the brazen vessels employed by the Greeks need not be introduced, "inasmuch," says he, "as all public theatres which are constructed of wood have many floors, which are necessarily conductors of sound."* Modern writers, it must be admitted, have not uniformly recognised the advantage of the employment of such materials, and some of them have maintained that the only assistance which the voice can receive from any quality of the building is from favourable reflections. It is hoped that what has been said has shown that this assistance is neither the only nor the most important that it is possible to afford; and in such accounts of existing buildings as will be shortly given, this point, among others, will be sought to be illustrated.

It may be noticed that in speaking of resonant materials wood has been referred to as if it were the only such material available for building purposes. This, perhaps, is not strictly the case, but the resonance of wood is so far more pliable, that is to say, ready to lend itself to *all* sounds, than that of other substances, and has so little "ring," or disposition to continue sounding after the original sound has ceased, that no material is comparable to it, or could replace it, even were it less available than it is for the purposes of the builder.

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* Vit. Lib. v., cap. 5, Rudimentary Series, vols. cxxviii. and cxxix. p. 3.

Cases will, however, occur, especially where fire-proof construction is deemed essential, where it may be deemed desirable to introduce a resonant material, and yet inexpedient to make use of wood. Probably experiment alone would determine how far, and by what means, these desiderata can be combined. Membranes stretched tight seem to offer an expedient worth considering, though the practical difficulty of keeping them always in uniform tension would perhaps prevent their applicability. The employment of thin plates of some hard metal, such as bell metal, in such situations as have at other times been filled in with panels of wood, suggests itself as an expedient worth trying, where an incombustible resonant material is required.

The only example* that bears upon this point seems to be the custom of the ancient Greeks, who, constructing their theatres of stone or marble, sought to reinforce the voices of the actors by the resonance of small bodies of air, which they enclosed in brazen jars, for which, however, they sometimes substituted vessels of earthenware, the reinforcing agent being not the material of the jar, but the mass of air contained in it. This expedient, and the possibility of adapting it to modern requirements, will come more appropriately under discussion, when we come to review the theatres of the ancients, but it will not be out of place here to draw attention to the fact that among ourselves there exists at least one familiar instance of a musical instrument in which, without perhaps knowing it, we reap the advantage of a system of *echeia* on an extended scale.

In the different stops of an *organ*, we have a series of pipes tuned either in unison, or as octaves or harmonics of each other; so that when a single note is sounded on a single stop there are at least as many silent pipes capable of sounding the same note as the instrument possesses stops, and four or five times that number to which it bears a harmonic relation; there can be no doubt but that resonance must be excited in some, perhaps in all of these pipes, by that note, and that to the blending of the mingled resonance of many quiet pipes with the note uttered by those actually speaking, we are indebted for the beauty and solemnity of tone exhibited by this noble instrument, and especially for the tone of single stops played unaccompanied. It follows that the presence of an organ in an orchestra or in a church, even when the instrument is not made use of, will be of some service to the tone of other musical instruments, or of the human voice.

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* The reflector in St. Paul's cathedral, described at p. 66, is, however, an instance of the successful application of metal to a purpose for which wood has hitherto been more commonly employed.

It is difficult to say whether the presence of resonant materials to the utmost possible extent, might of itself induce *excessive* resonance, but coupled with the sonority of the atmosphere, it may sometimes do so. This, however, is a fault on the right side, as it is easy to tone down any approach to excess by the introduction of carpets, matting, or cushions. It must also be remembered that an audience by their presence in a room diminish its sonority very much, so that such rooms as are excellent when full are liable to be found noisy when only partially filled. The Free Trade Hall and St. Martin's Hall present examples of this defect, if defect it can be called.

In passing to the resonance of the body of air contained in a room, we approach topics that cannot be considered as having been elucidated to any great extent.

It is just as true of a column or mass of air in a room as it is of that contained in an organ-pipe or a drum, that its actual volume, the dimensions and shape which it assumes, and the divisions that may be set up in it, all play a part in the production of any sonority that may exist, and in determining the nature and pitch of such sound, and consequently we should require for the full elucidation of the dangers to be feared or benefits to be obtained from the mass of air in a room, viewed as itself able to emit and to reinforce sounds, correct data, both theoretical and practical, relative to the nature of the undulations and vibrations that can be set up in large masses of air, and the influence upon them of the *proportions*, the shape, and the actual dimensions of the containing walls. Towards the furnishing of these data little has yet been done, and it will hardly be possible here to do more than indicate the general direction which such investigations as will throw light on this subject, may be expected to take, and to give a few obvious suggestions for general application.

The violin has shown us that an included body of air maintains its proper musical note with so much more persistency than the thin plates of wood in which it is included, that when the instrument is struck, or in any other way made to give out *its own note*, that note is the one proper to the mass of air, and not that proper to the tables of wood; and further, that under the influence of the vibrations of the strings, this mass of air is made to assist the plates of wood in reinforcing all the sounds produced by the performer; and lastly, that it does this most perfectly when it has a note in perfect harmony with the fundamental note of the strings. Now, a good room is in very nearly the same condition; any resonant materials that may be employed discharge the same functions as the walls of the instrument, and the included mass of air is also made to support the emitted sound, in the same way as that included in the violin.

The existence of the proper note of different rooms has long been recognised, and it may be fairly supposed that its purity, and perhaps its pitch, are as important as they are in the instance of the violin. The production of this note is due to the same laws which regulate the pitch of an organ-pipe, but with this difference, that in the majority of instances the note actually heard is only a harmonic, or a blending of several harmonics of the real note.* It would, no doubt, be very advantageous to have the means of securing that this note should be of some definite pitch, ascertained by experiment (as in the violin) to be advantageous, but failing that, it is very obvious, if the analogy with the violin hold good, that it will be of advantage for that note to be pure in tone; and, if it is possible, to show that good proportions in a room may be supposed, without a great stretch of imagination, to be conducive to purity in the note proper to that room, some light will have been thrown upon a fact admitted in common practice, more readily than accounted for in theory, namely, that such proportions as are pleasing to the eye are ordinarily satisfactory in their influence on the ear.

If in an empty room of some size we make any sudden noise, as, for instance, a stamp with the foot, it will ordinarily be possible to trace, as the sound dies away, the appearance of a musical note—the note under consideration. This is most probably occasioned by the recurrence of echoes from end to end, and from side to side, and from floor to ceiling. Suppose, now, that the dimensions of the room bear to one another some simple ratio—say that of height 1, width 2, and length 4—it will follow that the repetitions caused by these echoes will strike the ear of any hearer in any part of the room at equally recurring intervals. For instance, in a room 28 feet high, 56 feet wide, and 112 feet long, the echo in each direction would follow paths of which that from floor to ceiling and back would be 56 long, and consequently could be traversed 20 times in a second;† that from one side to the other and back would be 112 feet long, and traversed 10 times in a second; and that from end to end and back 224 feet, and traversed 5 times in a second. There would be other echoes audible, varying with the relative positions of the hearer, and the point where the sound was made, but the equable recurrence of those just enumerated would be what would excite sonorous agitation in the air. Now from the known property of sounding strings or columns of air to divide themselves into equal portions,* we may assume it probable that the waves thus produced would be subdivided into many shorter undulations by nodes; and a brief examination of the nature of our supposed room will show that this subdivision would only make the three sets of supposed motions coincide more frequently. For instance, the division of the longitudinal undulation into two would make it coincide with the transverse wave; its division into four would coincide with the vertical wave, or with the subdivision of the horizontal wave into two, and so on to any extent. As notes composed of five, ten, or even twenty repetitions in a second are not, however, ordinarily audible,† it is certain that the note of the room—if the hypothesis now thrown out be correct—will be higher than that due even to the vertical undulations supposed, but there is (in the absence of actual experiment) good reason to believe that this note would be a harmonic of the one due to 20 vibrations per second, that is to say, would have 40, 60, 80, or some similar higher number of vibrations, producible by subdividing the column of air by a given number of nodal points, and that it would be *pure.*‡

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* Ante, p. 10.

† Omitting minute fractions.

Supposing, however, the dimensions such, that reflections, as they successively strike the ear, come always at irregular and quite incommensurable intervals, that is to say that the pulsations passing and repassing from side to side will very seldom coincide with those passing from end to end, or from floor to ceiling, the result will be that, from the moment that the sound proper to the room, and excited in it by the echoes of any other sound, begins to appear, a noise, and not a note, will be audible.

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* Ante, p. 10. † Ante, p. 13.

‡ See Mr. Scott Russell's paper, reported in *Building News* for Dec., 1858.

Any badly-proportioned room, even if small, will display this noisy character; and some small and ill-shaped rooms seem to possess, in addition, a stronger tendency to emit sound, whenever they are spoken in, than is ever the case with shapely rooms.

This hypothesis may prove, after all, to be wide of the actual truth; and it will require careful experiments to decide; but it has at least probability on its side, and offers a possible solution of the difficult question of *proportion.* To those who may propose to attempt its further elucidation, the apparatus of Savart, already described,* seems to afford the means of investigating, with some hope of a profitable result, the condition of the air in a room. By means of this apparatus, Savart established,† beyond doubt, the existence of lines of greatest agitation in the air (and, consequently, of nodes); and his further discovery of the arrangement of them cannot be better told than in the words of Herschel. "If we carry an exploring membrane, such as already described, about the apartment, noting all the points where it vibrates most forcibly, allowing ourselves, as it were, to be led from spot to spot by its indications, we shall trace out in the air of the room a curve of double curvature, marking the maxima of the excursions of the aerial molecules. If the experiment be made in a gallery or passage, whose length is its principal dimension, this curve will be found to be a kind of spiral, creeping round the walls, floor, and ceiling obliquely to the axis of the gallery, thus presenting a marked analogy to the disposition of the nodal lines in a long rod vibrating tangentially, which are also, it should be remarked, imitated with modifications, more or less complicated, in square or rectangular rods."

"A still more remarkable effect was observed by M. Savart in thus exploring the vibrations of the air in an apartment with an open window. The spiral disposition of the vibrating portions was found to be continued out of the window into the open air, the lines of the greatest intensity running out in great convolutions, which seemed to grow wider on receding from the window, and could be traced to a great distance from it." *

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* Ante, p. 31.

† Ann. de Chimie, tom. xxiv.

A series of experiments, conducted with this or a similar apparatus upon the air of a room when so roused as actually to become itself sonorous, would probably yield valuable results, supposing it were practicable to obtain the necessary observations.

It may, however, be long before assistance of this nature will be available, and probably the best practical guide as to the proportions best suited for rooms, and the actual dimensions most advisable, will be obtained from a patient and careful collection of the principal dimensions of a large number of public rooms, or from observations made in an experimental room capable of being enlarged or contracted, and tested in every possible way.

Some remarkable instances of harmonic proportion between the dimensions of notoriously successful rooms, will come before us in the next chapter—especially Professor Donaldson's very successful rooms in Edinburgh, but the necessity for complying with other requirements, especially in cases where buildings occupy a limited site, and the difficulty in many cases, where rooms are not perfectly simple in form, of ascertaining exactly which dimensions are of importance and which are not so, will probably often render it impossible to adopt such proportions, and may even deter architects from making the attempt.

It seems probable that any accidental circumstances which favour the division of the vibrating mass of air into waves of

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* Ency. Metr., art. "Sound," secs. 333, 336.

equal length may assist the beauty of resonance; this idea seems suggested by the extreme richness of the natural sounds capable of being roused in our cathedrals and large churches where the uniform succession of piers and vaulting compartments seems to afford a system of obstructions at equal distances, the probable action of which will be to establish nodal points, and so favour the production of musical sound. Certain it is that, whether from this circumstance, or merely from the long column of air they contain, these buildings are unrivalled in the musical richness of the support which they afford to singing, intoning, or chaunting. Like the little mass of air in the violin, with which we started, this resonant atmosphere will lend itself to the support of any note or any chord whatever, although as the sound is dying away the proper note, or, more exactly, the proper chord, for it is generally a series of harmonic notes blended together which is heard, first mingles with and then overpowers the fading note that has excited it; and the way in which prolongation of the original sound passes into the one belonging to the building is one of the most beautiful of all the phenomena of sound; this is to be heard nowhere in greater perfection than in the choir of Westminster.

Canterbury is celebrated among our cathedrals for the influence it exerts upon sound; a note or a chord sung in some parts of that building will be heard for an extraordinary length of time, and as if slowly travelling round the whole church. The distinctness with which sounds are heard from end to end of the nave, has also been remarked by Mr. Scott Russell;* but in this respect Canterbury differs from most churches conspicuous for their musical resonance, as the very circumstances that so enhance the beauty of the music, and of the portions of the service performed in a manner adapted to such buildings, and no doubt devised to correspond with their acoustic requirements, render it often difficult to read and preach with distinctness, and so as to be audible to any great distance.

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* Paper before R. Inst. Brit. Arch.

We are thus led round to excessive aerial resonance, due to the presence of a very large mass of air, and are now in a position to advance, with tolerable probability, the opinion that such resonance will be the more obnoxious the less musical or pure it is. Probably the amount of sonority which a practised speaker can not only endure, but control in a cathedral, would render his speaking entirely inaudible in an ordinary room or an irregularly shaped building; and it is also probable that in a room lined with wood or other resonant materials, a certain favourable influence is exercised over the mass of contained air sufficient to permit of the presence of a large volume with comparative impunity.

In all cases, however, where distinctness of hearing and ease of speaking are the main essentials, and where musical effect is of secondary importance, it may be very confidently asserted that it is right to diminish the volume of air contained in the room to the smallest amount compatible with good proportion, and the preservation of free space for the sound to penetrate direct to every spot that it is wished to reach. Sound is, as has been already observed,* absorbed by empty space, since the larger the mass of air to be set in motion the greater demand upon the efforts of the speaker, whose voice ought always entirely to fill the room, and further, the greater the sonorous mass, if it be sonorous, the longer will its independent sound be maintained, and the louder will it be.

Consequently, rooms for public speaking ought to be *low* in proportion, if they are of the ordinary classes, *i.e.*, actually rooms where the main auxiliaries are conduction and reflection, and where the auditory occupy the floor, and, perhaps, a single gallery. If, however, they are buildings adapted to the unaided radiation of the voice, like theatres, and have the audience in tiers of lofty galleries, then they will with propriety be lofty, but as much restricted as may be in the area they cover. The one dimension, either of area or height, as the case may be, which can be diminished without trenching upon the accommodation afforded, ought always to be as much restricted as possible, for the sake of limiting the gross cubical contents of the building.

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* Ante, pp. 39, 40.

In this and the preceding chapter, as much has been said as to the science of acoustics generally, and the application of that science to the purposes of the architect, as it seems possible to advance. The general laws of sound have been considered, and the obstacles and auxiliaries which can exist in buildings have been passed in review. It only remains to consider, in the succeeding chapter, some instances of the application of these principles to actual practice; and before attempting this it seems appropriate to recall for a moment the scope of the observations made in one of the early paragraphs of this section.

Auxiliaries have naturally absorbed much of our attention; they are important in a high degree; there is a natural desire to know what can be *done* to favour sound; and there also can be no question that no very brilliant results can be achieved, no building can be erected that shall command an European reputation unless, in addition to perfect freedom from all defects, every available auxiliary has been brought to bear upon it, and form, materials, and proportions concur in exerting a combined and advantageous influence upon its acoustic qualities. It may be even advanced that the value of auxiliaries, especially the subtler ones of resonance and proportion, is very liable to be underrated, in consequence of the effects they produce being less tangible and less self-evident than are the injuries resulting from great defects. If a room be free from an amount of echo, and other defects, so glaring as to render it impossible to hear at all, many persons will hardly stop to inquire whether music sounds pleasant and speakers feel unconstrained in it or not; but the architect who wishes to accomplish the utmost that lies within his power must remember that, slight as is the difference between a dead and a brilliant tone, or between ease and effort, in that difference lies the whole question, whether his rooms shall be good or bad music-rooms, his churches the comfort or the bane * of the clergymen that do duty in them.

Auxiliaries, however, cannot be expected to produce their proper effect, unless a clear scope is secured for them; and it must therefore be always remembered that the first effort in arranging a building ought to be to avoid or remove all obstacles to the free progress of sound. This alone, when well done, will secure no inconsiderable measure of success, although it may not of itself suffice to produce a brilliant or even a complete result.

This negative precaution having been effectually taken, then, and not till then, every resource must be employed for reinforcing and sustaining sound, not overlooking even such auxiliaries as may seem too slight to be worthy of much attention, or too refined to be of practical utility by the side of others more obvious and more ostensibly serviceable; because it can only be by the combination of a number of agencies, each in itself contributing but a moderate and a proportionate share of advantage, that complete satisfaction will be attainable. The influence of even a valuable auxiliary may become injurious if pushed to excess or employed too exclusively; thus reflection may be expanded to echo, resonance may deteriorate into noise, a musical support to the voice may be exaggerated till it

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* See paper on Church Arrangement by Mr. Blomfield, in the *Builder* for 1860.

drowns all distinctness. It ought, therefore, to be our aim, not to make any building conspicuous for one excellence only, or to guard it against one defect, but rather to secure for it an equal proportion of every advantage within our reach, and protect it from every possible mischance, esteeming no fault too small to be injurious, and no advantage so insignificant as not to be worth an effort, no matter how great a degree of excellence may be reasonably supposed to have been already secured.

SECTION III.

APPLICATIONS.

In attempting to point out the practical application to be made of the theoretical principles which it has been attempted to educe, the most useful method will, it is believed, be as far as possible to combine into groups those buildings or classes of buildings which in relation to sound depend upon the same great principles for their success, and then to explain in succession the properties of the various classes of buildings included in these groups; adding in illustration descriptions of a few celebrated examples, and showing in what respects they bear out the views laid down.

It must at the same time be borne in mind that it is one thing to examine the characteristics and qualities of an existing building, and to trace their conformity to general laws, and another and a more difficult one, possessing the general laws only, to apply them with certainty and success to the treatment of a projected building. In this art, as in many others, the best method of becoming familiar with the value of theoretical maxims is to bring them to the test afforded by a comparison with actual practice.

The variety observable in the disposition of all the essential parts of buildings for public purposes depends upon the fact that the destination of a large public building is seldom such as to leave its form, proportions, and materials entirely free to be fixed according to the laws of sound. Ordinarily a multitude of other circumstances give a decided character to all these, and the consideration of what will favour hearing has to be combined with preparations for filling up other parts of a settled programme. This is why it would be insufficient merely to devote a little attention to the general application to buildings of the principles just laid down, and becomes requisite to consider the special requirements of individual instances.

The course about to be taken having now been announced, it may serve the convenience of the reader, if he be here informed of the order in which public buildings will be arranged.

We propose, then, to commence with buildings in which the voice spreads wholly or chiefly by direct natural radiation, and in this category shall have to consider the theatres of the ancients, modern theatres, lecture rooms, and courts of justice. We shall next pass to buildings where sound is directed, preserved, or conducted, and shall commence with ancient basilicas, and then notice in succession modern churches and other places of public worship, halls, and large and small rooms. Some remarks on such irregular structures as cannot be classed among the above, and a few concluding observations, will then be all that it will be necessary to add.

Some writers, including the author himself, on a previous occasion* have divided buildings, according to their *size*, into those which lie within and those which exceed the dimensions limiting the natural radiation of sound. Such a division, however, does not place the question in the clearest light, and the classification resulting from its employment, though frequently coinciding with what seems the most natural arrangement, yet sometimes departs from it.

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* Paper before Architectural Association.

If, regardless of dimensions, we divide structures into those where radiation of sound governs the form, and those where the directing and preserving influence of the walls and roofs does so, we shall have two essentially different groups—groups which, without much violence, we might distinguish as the natural and the artificial, and of which the characteristics are mainly these.

In the buildings where sound is directly radiated from the speaker to the hearers much as in the open air, the outline of the building approaches a circular or semicircular shape, the extreme limit of the building being for the greater portion of its extent about at the same distance from the speaker, and, the area being restricted, the seats are disposed either in an amphitheatrical way or in galleries:—such buildings may be lofty, and often are so.

In the buildings where the sound is directed by, or conducted along walls and ceilings, preserved by them from lateral escape, and aided by reflection from them, the form of the building combines with the initial impulse of the sound, and conducts it onwards in one direction.

Such buildings are therefore necessarily oblong, they usually ought not to be lofty, and they are commonly rectangular on plan.

It will be found that ordinarily one or other of these principles, with the attendant proportions here described, ought to prevail in every structure, though of course there will be instances in which a building will partake of some of the properties of both groups; such instances are, however, not numerous.

It will also be found that the auxiliary aid of resonant materials, and that of reflectors behind and above the speaker, are available in the structures of both groups. The consideration therefore of the possibility of applying these two modes of helping sound ought to enter into the calculations of the architect upon every occasion.

Lastly, as has already been hinted, the limit of size is not easily fixed (if any such limit really exists), which will render the employment of one or other principle obligatory, for though the principle of conduction (or artificial arrangement) seems to promise to afford a means of enabling larger audiences to hear than it can be hoped that the human voice, however well supported, could reach by direct radiation, yet one of the best known authorities on the subject * has considered as practicable the erection of a building similar to a theatre in general shape, and consequently depending mainly upon natural radiation of sound, within the walls of which an audience could find accommodation and would be able to hear, more than twice as numerous as there is any reason to believe has ever been addressed at one time in any room, of oblong form, and constructed to favour the artificial preservation and conduction of sound.

I. Buildings in which the voice spreads wholly or chiefly by direct natural radiation.

If we endeavour to imagine under what conditions a speaker might address a large auditory, so that the sounds of his voice should reach every hearer as directly as possible, and as free as possible from interference or echo, it can hardly fail to strike us that the wall enclosing the audience ought to follow an outline, similar to that of the flattened circle obtained by Saunders' experiments,† and that the speaker ought to occupy a nearly central position, there marked by the letter A. What was subsequently said, ‡ on the method of avoiding obstructions will lead us to arrange that the seats shall

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* Mr. Scott Russell before Institute of British Architects.

† Ante, p. 34.

‡ Ante, pp. 43 to 46.

rise one behind another like steps, those at the back being the most steep, and that the position of the speaker shall be a little elevated. Convenience of arrangement and the necessity for allowing every one the best opportunity of directing his eyes upon the speaker will both dictate a concentric arrangement of seats; and, finally, the desireableness of preserving a space for the entrance and exit of the speaker, or for the exhibition of objects that have to be beheld by the audience, will induce us to omit the seats behind the speaker, where, indeed, auditors would be perfectly unable to watch his face and gestures, though they might hear him well.

The speaker will now find himself the focus of something like a hollow sphere of listeners, not too remote from even the most distant to be distinctly perceived and heard, and as he turns from side to side, alike open to the gaze of every hearer in the building, and himself enjoying perfect command of every face before him.

All these requirements have never been so successfully, perfectly, and simply attained as in the theatres of the ancients; and we take a Greek theatre * as the most perfect type of the amphitheatrical class of buildings, the class in which the auditors hear principally by direct natural radiation of the voice, and of which the distinctive features are stepped seats on section, and a curved outline on plan. The seats for the audience in a Greek theatre were of stone, often hewn out of the live rock, and were ranged amphitheatrically above and behind one another, and swept round in a curve considerably more than a semicircle, stopping against a lofty wall, with a deep and wide central recess in it, which formed the scene. The stage, elevated to a considerable height,

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* See for descriptions and plans of various ancient theatres, the illustrations to Gwilt's Vitruvius, Rudimentary Series, vols. cxxviii. and cxxix; Saunders on Theatres; Smith's Dict. of Greek and Roman Antiquities; Strack's Altgriechische Theater-gebäude; and the supplementary volume to Stuart's Athens.

occupied the space in front of this central scene. From it, but at a lower level, projected the orchestra, on which the chorus with their leader were placed, and from which they sang. The chorus was originally the most important part of a Greek drama, and hence to it this central situation was assigned—the very best one possible for being seen and heard. Behind the seats was a lofty enclosing wall, often with a range of columns against the inner face.

The theatres of the Romans were similar in general arrangement, the principal difference being, to quote from Smith's dictionary, "that the seats of the spectators, which rose in the form of an amphitheatre, did not form more than a semicircle, and that the whole of the orchestra likewise formed only a semicircle, the diameter of which formed the front line of the stage."

Over the auditory was stretched, as a protection against the sun's rays, a vast awning called a "velarium," and this, it may be fairly considered, tended a little to prevent the dispersion of the voice. A very good idea, both of the velarium and of the auditorium or audience part of a Roman theatre, may be obtained by inspecting the Great Handel Orchestra in the Crystal Palace. This is similar in form and arrangement of seats to what we have been describing; and if a lofty wall with a recess for the stage be supposed to be built in the nave of the Palace, as high as the enclosure behind the highest range of seats, and the parallel to the present front of this orchestra, but someway back, a stage being formed behind the spot at present occupied by the conductor's place and the seats near it, a good general idea will have been formed of one of those vast yet commodious structures.

The most ancient of these erections were of wood, and in Greece after a time the wooden ones were entirely replaced by new and splendid buildings in stone or marble; but from Vitruvius, as well as other authorities, it appears that in Rome theatres were even till a late period customarily constructed of wood; and as has been already remarked, he assigns that as a reason why vessels to reinforce the sound were not needed in them. In the stone structures it was found that the support which the voice receives from resonant substances, a support closely resembling that which a singer derives from an instrumental accompaniment, was not afforded as it had been in timber buildings, and the expedient was devised of introducing resonant vases, termed echeia ('Ηχεῖα), and formed usually, but not always, of bronze. They were fixed in open-mouthed cavities prepared for them under the seats of the theatre; the capacity and form of the vessels being such, and so graduated, that the contained air in them would give forth a musical series of sounds when set in vibration.

Vitruvius prescribes * that, in a theatre of moderate size, a zone of thirteen of these cavities shall run round at half the height; but adds, "if, however, the theatre be on a larger scale, the height is to be divided into four parts, so that three ranges of cavities may be provided, one for harmonic, the second for chromatic, and the third for diatonic vases."

To some who have asserted that the echeia † cannot possibly have produced any beneficial result, it might be almost a sufficient reply simply to recall the admitted skill and intelligence of the Greeks, and to point out how unlikely it is that such an arrangement would have been repeatedly made use of unless proved actually to be of advantage, showing that although that advantage may have been of a refined and delicate nature, it must have been actual. This expedient, moreover, notwithstanding that it has excited con-

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* Lib. v. c. 5.

† Chladni, Traité, s. 209. For a more complete description, and a condensed account of the opinions that have been expressed on this subject, consult the Dictionary of the Architectural Publication Society, under the head Echeia.

troversy, and even ridicule, seems to have been founded upon sound principles; for it was pretty certain that the voice of a speaker or singer would find at least one resonant cavity to support it, and probably several. If the view held by some be correct and the dramas of the Greeks were not spoken, but declaimed in a sustained musical note, like modern recitative, it would be easy for the notes of these vessels to be called forth by the voice, and to render powerful support to it. Within the last few years some of the incidental dramatic music written by Mendelssohn has been performed in this country, associated with passages of blank verse, that are intended to be declaimed in a sustained slow tone, more solemn and with less of musical phrasing than a recitative, and supported by an accompaniment on brass instruments. The effect of the slow dignified monotone thus accompanied is majestic and impressive in no common degree, and suggests what may have been the effect of the measured and semi-musical declamation we have alluded to, supported by the hollow resonance of echeia, as the modulations of the speaker's voice called one after another of them into play.

Almost any amount of resonance could be permitted to accompany an utterance of such a character, even to an extent that would totally confuse a spoken address delivered with the ordinary degree of variation in tone, and at anything like ordinary speed. We may, however, conclude that the employment of such echeia is not likely to be suitable in modern buildings intended for ordinary speaking. This view seems incidentally supported by the fact that there is no trace of these vases, or any substitute for them, ever having been introduced into basilicæ or fora.

The only case in which a mode of enunciation, analogous to that for which we suppose the echeia to have been adapted, is now in use, is in the intoning of masses or choral services, and ordinarily this takes place in buildings where the air is abundantly resonant without artificial means. Should, however, an instance occur in which support to the voice is needed in a non-resonant church, where intoning is practised, it seems rational to believe that open vessels constructed and employed in the same manner as the echeia would be beneficial.

Before leaving the subject it may be desirable to inquire whether any assistance was afforded to the voice in these structures by other auxiliaries than the unquestionable resonance of the timber in the wooden structures, and the less obvious support of the echeia.

Vitruvius, among his directions relative to a theatre,* prescribes that attention must be bestowed on the choice of a place, where the voice falls smoothly and reaches the ear distinctly without an echo; he then goes on to describe different kinds of action which in different localities modify the sound of the voice, and concludes thence that "if due care be taken in the choice of the situation the effect of the voice will be improved, and the utility of the theatre increased." However this may have been, it is not easy for us now to determine, but there seems no sound reason for doubting that to a building so open to external influences as an ancient theatre, hewn as it often was out of live rock, or built into the side of a hill, the natural advantages of the locality selected might be very beneficial. It is very clear that the velarium must have exerted a slight influence on sound, but whether it would not do harm by deadening it as well as good by preventing its escape, may be very fairly questioned. There seems, however, no ground to doubt that some amount of favourable reflection took place from the lofty wall behind the stage, forming the scene with its two advancing sides. In the ancient theatre at Orange this wall remains in a very perfect state of preservation, as well as the seats; and it is difficult to visit that building and try the voice in it without being impressed by the belief that this lofty wall and its wings, enclosing the shallow stage, play a most important part in securing the remarkable facility of hearing and ease in speaking which distinguish that building.

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* Lib. v. c. 9.

In the works of Rhode * mention is made of the ruins of "a theatre at Athens," the back of which is less than a semicircle, and of which the two sides are bounded by walls radiating from a point behind the back of the stage. The attempt to identify this theatre has not, however, been successful, unless the ruins of the Pnyx are referred to. The Pnyx was a public place where large popular assemblies were held, and the area it covered is stated to have been 12,000 square yards.† The outline of this building shows that at the back of the seats of the auditors there ran a semicircular wall like that of a theatre, the bench from whence the orators spoke occupying a spot at the centre of this sweep, at the ends of which were two walls which met in a very obtuse angle behind the speakers, in place of the one wall breaking back in the centre which was ordinarily seen in theatres.

Almost all modern theatres for dramatic performances have abandoned the stepped arrangement of seats, while retaining, though with modifications, something of the outline of those of the Greeks and Romans; but there has risen up a class of buildings, more nearly analogous than these to the ancient models, and which it will consequently be expedient to consider first—these are lecture theatres, often termed, though without perfect accuracy, amphitheatres.

This class of buildings has been ably examined and illustrated by Lachéz,‡ and he gives an examination of the

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* Akustik, p. 41 ; Chladni, Traité, p. 208.

† Smith's Dict. (Plan in supplementary volume of Stuart's Athens.)

‡ Acoustique et Optique, pp. 85, 105.

principal amphitheatres in Paris, and points out their defects, the most serious one being ordinarily an injurious redundancy of space.

Among English lecture theatres one of the most celebrated was that built by Wren for the College of Physicians. This building having seats on all sides, may justly receive the name of an amphitheatre. It stands in Warwick Lane, Newgate Street, and now forms part of Messrs. Tyler's iron foundry. It has been a good deal dismantled, but was carefully illustrated by engravings from the measurements of Professor Cockerell, published with a descriptive account, in Elmes' Life of Wren. This theatre had an internal diameter of 40 feet, and was of a regular 16-sided figure, lined to a considerable extent with wood; the lecture table was in the centre, and was quite surrounded by the seats, which rise steeply and on a sort of isacoustic curve. The wall above them is not lofty, and is surmounted by a flattened dome with a large central lanthorn. This interesting and well-arranged building has long been out of use, and was never intended for an extremely numerous audience, but probably was as good for both seeing and hearing as could possibly be desired.

As an example of a lecture room closely resembling the Greek and Roman theatres, and accommodating large numbers with success, we now turn to the justly celebrated theatre of the Royal Institution in Albemarle Street. Professor Faraday, in evidence before a committee of the House, at the time the rebuilding of the Houses of Parliament was being proposed, stated that this building will seat 800 persons, and that he considered it as almost perfect for a single speaker. It was also adduced by Mr. Scott Russell in his papers as an admirable example; and the only difficulty ever complained of is that when quite full, there is occasionally a little effort requisite to reach with the voice auditors quite at the back, under the gallery, a thing not to be wondered at, when the extremely narrow space through which only the sound can arrive at those persons is taken into account. The architect was Mr. Webster, and it is said he was assisted by Count Rumford and Sir Humphry Davy.

We give a plan and section* of this lecture theatre; and on endeavouring to find out the causes of its excellence, it will be observed first, that the principal dimensions are in the very simple relation to one another of 2, 3, and 4, the height, depth, and breadth being respectively, within a few inches, 30, 45, and 60 feet.

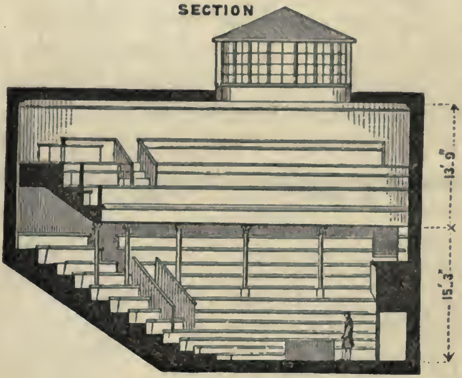

Fig. 13.

Next, the spectators are brought near to the speaker, only 2 feet being allowed from back to back of seats so that the volume of air contained in the entire structure is not large, and thus very little of the voice is lost.

Thirdly, the seats are all elevated on a curve similar to that proposed by Mr. Scott Russell; and this, coupled with the moderate size of the room, secures to each auditor a direct ray of vigorous sound, and an uninterrupted line of sight, as has been explained.

Fourthly, and principally, the whole place is constructed of resonant materials, the semicircular sweep being formed entirely of wood, built within a square space enclosed by the brick outer walls; the two spandril-shaped places so formed being occupied by staircases.

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* From measurements taken for the purpose.

There are rooms underneath the floor, and all the benches, seats, steps, &c., are entirely of wood; the ceiling and part of the wall behind the speaker being the only plastered surfaces visible. This circumstance gives a pleasant but not overpowering sonority to the room when empty.

The only suspicious feature in the whole structure is the skylight, but that is circular on plan, so that the resonance of a cubical box is avoided; there is, however, a slight echo perceptible when standing just under it, and in front of the lecture table, but nothing of the sort when standing in the proper place for the lecturer, behind the table.

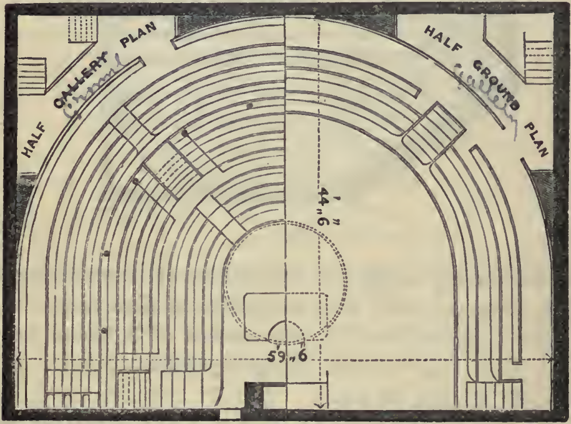

Fig. 14.

Were a room to be built similar in plan, but with much more space at the sides or behind the speaker, the large masses of air would be found injurious; this is actually proved by the theatre in the Jardin des Plantes, at Paris, a building similar in plan to the one now under consideration but larger in size, and with a great space added behind, though not seating more persons. Lachéz, who gives a plan of it, says that the hearing is, from this cause, defective. Inattention to this economy of space, to the employment of resonant materials, and to the proportion between the dimensions of the room, may have been the causes why several buildings said to have been constructed on the model of the theatre of the Royal Institution, have none of them equalled it.

If it be inquired how the vacant space near the speaker can be best destroyed, it is only necessary to watch, as they gradually fill, the benches of a room of this nature, on any occasion when all are very desirous to see and hear well; it will be found that the seats opposite the speaker are all occupied, even if they be remote, before the side seats are taken, so that the crowd will form something of a pear-shaped mass.* Under such circumstances the expedient can hardly fail to suggest itself of cutting off space at the sides of the speaker, by side walls placed diagonally, and adding a little additional depth to make up for the area so lost. The form now arrived at † certainly combines the advantages of the contraction of space near the speaker, and of surrounding him with favourably disposed reflecting surfaces, while it probably also introduces some amount of favourable conduction. Should we proceed further, and place a sloping ceiling over the speaker's head, and take care to construct the whole of sonorous materials, the seats being arranged on an isacoustic curve, a structure extremely favourable to success in speaking will have been arranged; and there seems no reason to doubt that a prodigious lecture theatre of this type might be successfully built.

The next step will naturally be the consideration of modern theatres, and it is not quite creditable to the science of architects, engaged in other branches of practice, that with hardly an exception, the whole of the few books written on the application of acoustics to architecture have exclusive reference to this class of buildings.

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* Lachéz, Optique, p. 69.

† That of the Pnyx.

The modern theatre most closely approaching in form the ideal cf an auditorium just now proposed, is the celebrated Teatro Farnese, in the ducal palace at Parma.* It is constructed entirely of wood, and was built A.D. 1618, but not opened till A.D. 1628. Saunders, who visited it previous to A.D. 1790, found it disused and in a decaying state; and at present it is rapidly approaching ruin. This theatre at Parma has often been referred to in books on sound, and is not to be confounded with the modern ducal theatre in that city. The architect of the old structure is not known, but Bernini is said to have completed it. Woods, in his "Letters of an Architect," observes that it "is neither very beautiful nor convenient, but very remarkable on account of the distinctness with which one hears even a low voice on the stage through every part."

From the account given by Saunders, it appears that the dimensions of this building were very considerable, as much as 130 feet long to the opening of the scene, by 102 feet wide, and that its form was oblong, rounded off at the end opposite the stage. The seats rise their whole height above each other, and are terminated by a magnificent corridor like Palladio's Basilica at Vicenza; and notwithstanding that between them and the stage there is a considerable vacant space, with rich triumphal arches on either side, the acoustic qualities remain good. The building contracts in width just in front of the stage, which is advantageous, and its seats are arranged amphitheatrically, which is also a good arrangement; but here again the most noteworthy circumstance is the material. "The interior part," remarks

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* See Saunders on Theatres; Woods' Letters of an Architect; Murray's Handbook to Northern Italy. Saunders gives a plan.

Saunders, "is wholly composed of wood; the ceiling is contrived of boards perfectly level and smooth.

"This theatre is universally cited as an admirable instance of the conveyance of sound, the truth of which I can testify; having conversed in a low voice from the stage to the opposite extremity. I found but little difference by retiring 10 or 12 feet on the stage; but beyond that the voice perceptibly varied, so that the proper (extreme) distance between the speaker and hearer was 140 feet. This extraordinary circumstance is generally allowed to be occasioned by the material with which it is lined. The boards are not placed horizontally, as some have imagined to be necessary for this purpose, but nearly all against the walls are perpendicular. Some, indeed, object that these advantages are not real, and that were the theatre filled with spectators, the absorbing materials of the clothes, bodies, &c., would destroy the effects. I can only answer that this theatre was played in so long as the court remained at Parma to maintain it; that had it been defective, that character could not have failed being somewhere mentioned; instead of which we ever find the same uniform account of its effects."

Where it is required to construct a theatre for a very large auditory, the stepped seats must be abandoned, and the ordinary arrangement of several tiers of boxes and galleries one above another resorted to, on account of the much larger number who can thus be accommodated on any given area of site. This is the form of building now universally erected for dramatic performances, and the little tract by Rhode already referred to contains many excellent general rules and suggestions, the spirit of which may be considered to be comprehended in the following extracts from Chladni's work:* "Rhode, in his treatise elsewhere quoted, remarks

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* Akustik für Baukünstler; consult also B. Wyatt on Principles of Design for a Theatre.

that the majority of theatres are but little favourable to sound, because the laws of the propagation of sound in tubes with parallel walls and in speaking-trumpets, have been too much neglected. The side boxes, near the stage, are very disadvantageous, as they absorb the sound to too great an extent. It would be better for effect if at the sides there were only straight walls, either parallel or diverging, and without decorations in relief. The ceiling ought not to be too high; it may be parallel to the pit, rising gradually towards the part of the house the most remote from the stage. The end opposite the stage may form a segment of a circle. The well known great theatre at Parma may serve as an example, but for still larger * theatres diverging side walls would be preferable. . . . M. Rhode also remarks that the ordinary arrangement of slips is contrary to the propagation of sound, because they absorb the sound which spreads laterally. . . . . The semicircular or semi-oval form ordinarily given to theatres is one adapted to contain many persons at a moderate distance from the spot where the sound is produced, but the form of an ancient theatre at Athens with divergent side walls (query the Pnyx?) could contain a still larger audience at the same distance."

A large part of these maxims is illustrated by Her Majesty's Theatre in the Haymarket, London, the old opera house which no building in Europe is said to surpass, if any equal it, for perfect diffusion of sound.

The plan of this building presents an end a little more than a semicircle, prolonged by two almost straight sides, which gradually approach each other as they reach the proscenium. The stage is remarkably shallow behind the curtain, but is advanced far into the house, so that any singer who is at its front has the audience all round and even partly behind him, and the orchestra being in front

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* Traité d'Acoustique, s. 210 and 208.

of the stage is even more among the auditors. There are no columns or other ornaments about the proscenium; and the ceiling, which is a flat segmental curve in part, is brought down towards the opening of the stage, so as to throw the sound forward; and there is no roughness on the faces of the boxes, which are perfectly plain, flat faces, devoid of all moulding or projection.

In short, the form is favourable for sound; the space above, behind, and at the sides of the stage is restricted as much as possible, and gradually swells out into the body of the house; while the divisions of the boxes, which do not radiate from the stage, would prevent any echo from the back wall, and break up any wave of conducted sound. More important, however, than all the favourable combinations of form presented is the circumstance that again the whole interior, including fronts of boxes, divisions between them, the gallery, and even the ceiling, is formed in wood; the audience are almost as though they were within some gigantic violin, and the whole included atmosphere were alive with the musical vibrations of its walls.

These walls are placed in the most favourable conditions possible, for the pieces of thin wood with which they are lined were procured in the longest lengths obtainable; there is an unoccupied hollow space above the ceiling, between it and the floor of the painting room, and a similar hollow space under the floor of the house. The fronts of the boxes, of which there are six tiers, recede gradually as they rise, and all projections and breaks have been studiously avoided, the decorations being all painted, in distemper.

It appears that various experiments were tried both during the erection of the theatre, and after its completion, particularly in the orchestra, the whole floor of which was at one time suspended entirely by strong framings, at the sides, prepared on purpose, in the expectation that the effects of its freedom might add to the power or melody of the instruments. That the plan did not lead to a satisfactory result may be inferred from its abandonment.

The scanty list of works on the application of acoustics to architecture, includes several books on the special subject of theatres. Among these, those of Rhode, Saunders, and Wyatt deserve special notice. There exists * also a very elaborate account, illustated by a series of engravings, of the King's Theatre at Berlin, in the design of which the architect, Ottmer, paid particular attention to acoustics. He states that his proposed arrangements received the sanction and approval of Chladni, and that their success was decided; but in the absence of independent testimony to the efficiency of the theatre, it does not seem needful to reproduce here the description of the building, which, after all, was not of extraordinary size, being only calculated to seat 1,570 spectators.

Before leaving the subject, it may be appropriate to draw attention to a fact which seems noteworthy as illustrating the value of hollow spaces under the floor of a building, where it is of importance that sound shall be well heard. It will be recollected that in continental theatres, especially in those of Italy, it is the practice to construct a sort of chamber with thin sides under the floor of the orchestra, with a view to increasing the resonance of the music; no decisive statements as to the results of this plan have been however met with, but there seems good reason to believe that it is beneficial, notwithstanding that Lachéz,† rather unreasonably, denies the possibility of any advantage from it. Less uncertainty, however, attends the results, whatever difference of opinion there may be as to their cause, in the following case, which rests on the authority of Dr. Hutton, and has been copied from him by other writers. He states that circumstances rendered it necessary to carry a canal of water under the floor of the Teatro del Argentino at Rome,

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* Architectonische Mittheilungen. † Acoustique, p. 59.

some time after its completion, and that the hearing, which up to that time had been very indifferent, became remarkably improved after the alteration. This change is usually attributed to some influence the water must have had upon the sound, though it is not quite easy to see what that influence can have been. Without, however, denying that the canal, filled as it was with water, *may* have had a more beneficial influence than it would have had empty; it seems more reasonable to believe that the main cause of the alteration was, notwithstanding that the work was solidly done, the establishment of a large empty resonant chamber under the floor, and increased elasticity in the floor itself, which it is fair to assume rested on supports close together, and near the ground, before the canal was introduced.

The last buildings it is proposed to include in the first or amphitheatrical group will be law courts. They are ordinarily furnished with stepped seats, more or less satisfactorily arranged, but hitherto have very seldom had at all a curved outline on plan, a fact perhaps due to the severe architectural expression that it is thought they ought to possess.

Law courts are commonly in the present day kept far within the dimensions that limit easy direct radiation of sound, but they do not seem to have been established on a very happy model.

Instead of approaching a semicircular outline, they have usually been made rectangular rooms, and frequently of the worst of all possible forms, cubical, or, when not quite that, almost always too nearly square on plan and too lofty, and with no arrangement for either narrowing the width or height of the court in the portions adjacent to the bench. The number of persons whom it is essential to hear perfectly in a court of law is not very great, and they are all grouped tolerably close together; but for these—namely, the judge, the jury, the accused, the counsel, and the reporters, as near an approach to perfection in hearing as is possible is demanded. Nor is it too much to expect that when these few persons occupy but a small portion of a not very large court, the architect should be able to provide for them satisfactorily. The principal difficulty seems to be presented by the fact that the audience is very crowded, and consequently the surfaces apt to deaden sound are numerous; and that the necessity for a large supply of air makes height in the court house desirable.

In order to secure success, the space behind and above the bench should be diminished as much as possible, so that in fact the business of the court would be conducted in and in front of a kind of recess, and this recess should be lined with well seasoned wood. The audience part of the court may be made loftier, and should have the seats arranged amphitheatrically, with a curved wall at the back, connected with which columns or recesses would be quite admissible. Indiarubber or matting should be employed, as is now sometimes done, to deaden any little sounds arising among the auditory, and the great quantity of wooden enclosures, like old fashioned pews, now in use, should be as far dispensed with as possible, as from the flat surfaces they present, they may be apt to cause reverberation when unoccupied. Sharp angles should be avoided, and so should deep skylights, and if a gallery is adopted it should not have an excessive projection. Lastly, it may be useful to observe that it is desirable to have the fittings about the bench moveable, especially the witness-box, so that the peculiarities of hearing in different judges may be met, and the witness and jury boxes placed where the judge wishes them. It seems probable that the heavy curtains and large cushions usually placed near the judge could be advantageously dispensed with. It might, on the other hand, be well to hang with curtains the wall behind the auditory so as to prevent any echo from it, even in addition to the columns, piers, niches, or other architectural features, which it has been suggested may be introduced for the same purpose into this part of the structure.

II. Buildings in which the naturally radiated sound is supplemented by sound "directed by or guided along walls and ceiling, preserved by them from lateral escape, and aided by reflection from them" form our second group.

The transition is in one sense a natural one, from the consideration of modern courts of justice to that of the classic basilicæ, the buildings in which the ancients administered justice; but the structures themselves are as dissimilar as it is well possible for buildings intended to serve the same purpose to be, and this very contrast will serve to illustrate the difference between the two great groups, into which we have divided buildings for public purposes, namely, those depending upon natural radiation of sound alone, and those depending in addition upon artificial direction and support of sound.

A basilica is believed to have commonly served the double purpose of a judicial court and a place for the transaction of commercial business, but all its arrangements had reference to the first-named destination. At the time of the public recognition of Christianity by Constantine, the existing basilicæ were found the most suitable buildings available for consecration to purposes of public Christian worship, and as a consequence they formed the models upon which the early churches were built; and their name as well as form descended unaltered to those churches.

In architectural and structural arrangements then the basilica may be taken as the typical form of nearly all the great buildings that have been erected during the last fifteen centuries for purpose of Christian worship.

In basilicæ and basilica churches there was invariably present the same arrangement that we have urged as desirable for modern law courts, namely, a large recess, for the president and his assessors occupying the end of the building. This was the original of the chancel in our modern churches, and in the basilica was of semicircular plan, with a central seat for the presiding judge, which in adapting the building to Christian uses was employed without alteration as the episcopal chair, and on the right and left of which were seats for those who assisted.

The main building was always of simple design, oblong, and divided by two rows of columns into a nave, with two side aisles; arches sprung from the columns, supporting two longitudinal walls which sustained the wooden roof over the nave, and two sloping roofs leaning up against these walls covered the aisles. The whole building was lighted through a clear story of windows over the nave arches.

In basilica churches there were built near the arch, which gave access to the apse, two *ambos,* the positions, and to a great extent, the purposes of which are still retained in our pulpit and reading-desk when in the place they usually occupy.

Among the basilicæ of Rome are some of such enormous length that probably no voice could entirely fill them,* nor were they extended to such dimensions with a view to their being ever entirely occupied by persons listening to speaking or preaching; but the form is no doubt well fitted to preserve the sound from decay, to direct it into a course along the length of the building, and to assist it in that course; and the moderate proportions in height of the ancient basilica were more favourable to this result than those adopted by the more daring constructors of the middle ages.

Before discussing churches as we now have them, and places of worship which have entirely thrown aside the traditions of basilica form, it will be well to draw attention to such of the requirements of a modern place of worship as will point out where such a building differs essentially from those places of public entertainment or instruction that have been already described under the head of buildings in which sound spreads by natural radiation.

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* St. Paolo fuori le Mure had an extreme length of 411 feet; Sta. Maria Maggiore is 280 feet in length by more than 50 feet in width.

In a theatre a not unimportant essential to the entertainment is that the audience should see each other, so as to allow all who wish it an opportunity for personal display, and for scrutinising the appearance of others. In a lecture room there is no objection to such an opportunity existing, nor can it be of prejudice to a law court. In a theatre, again, it is essential that a variety of classes of accommodation should be preserved, and conspicuously separated one from another; and this also is or may be done to some extent in a lecture room, and in a court of law.

In a place of public worship, however, it is in the last degree undesirable that the opportunity should occur, either for display and scrutiny of one another on the part of any portion of the congregation, or for ostentatious separation of their seats into different classes.

Consequently, anything which causes part of the congregation to sit facing another part, anything that elevates one seat above another, and, more than all, anything that exposes a whole range of persons to the scrutiny of any or every eye among themselves is essentially unsuitable; thus rendering a level floor all but indispensable, and a circular or other allied form of building almost inadmissible.

In modern Protestant churches and chapels it is at the same time very necessary that every person should be able easily to hear the speaking or reading voice of a single individual, and he, unhappily, but too often badly trained or entirely uninstructed in the management of the voice, or art of public speaking;* and that all should with ease be able to direct their looks in the same direction. Obviously the best building for this purpose will be an oblong building without galleries, with the congregation all arranged on a level floor, and their seats fixed all to look towards one end.

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* It is necessary for the architect to remember this; for if in arranging a church he calculates upon the preacher's being as much master of his voice as the members of other professions in which public speaking is the main feature, he will frequently find his expectations disappointed.

Should the necessity for seating a large number be pressing, there can be but little danger of undesirable display or publicity in an end gallery, the occupants of which will be looking in the same direction as those below; though there is some ground for objection on the score of a distinction of places and a division of the congregation. Side galleries where introduced are open to both objections; at times, however, they are indispensable, but the custom which is sometimes followed of giving an amphitheatrical, semicircular sweep to the end gallery, where there are also side galleries, is never essential, and is a great aggravation of the evil of these features, for the simple reason that it displays a large portion of the congregation in a much more prominent way than need or can occur, if the end gallery have a straight front.

It is proposed now to consider churches and chapels built with a nave and aisles, and if it be admitted that an oblong building with, or, if possible, without galleries, is desirable for purposes of worship, there are various reasons, besides that of ancient usage, why the arrangement of a nave and aisles should be one of the best for such a structure; not the slightest of these reasons being that even if the building be necessarily nearly square on plan it gains the appearance and, to some extent, the acoustic qualities of an oblong structure by the introduction of the columns; though under these circumstances it must not be supposed that a very powerful influence is exerted upon sound in the way of directing it, and preserving it from decay, such as seems to exist in some buildings of great length compared with their width.

This influence, undoubted as it is, and considerable as its effects are in certain cases,* is probably in the majority of small and middle-sized structures but feeble; and the practice of the most successful church builders seems to show that it is not prudent to rely upon it, when moderate numbers only are to be accommodated, in preference to the more obvious method of limiting the dimensions of the building, and placing the auditors as close to the speaker as possible.

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* *E.g.*, Canterbury Cathedral.

It will be found that in the very large churches of the middle ages, the vault is far too lofty to assist in the transmission of unaltered sounds. The object of raising these was not to build a church just so large as a single speaker could fill with his voice, but to raise a monumental pile for great ceremonials, and it was of no moment that the resonance of the contained mass of air should be great, so long as it did not impair the effect of music. Accordingly the sonority of most of them opposes a serious obstacle to their being used for preaching. The plan adopted on the continent is no doubt the best for such cases, and a pulpit must be erected against a column of the nave overshadowed by a large sounding-board, while the congregation are left free to form themselves in front at the sides, and even behind the pulpit, into a large group round the preacher. The direct assistance given by the building to the voice will not be very great, but a skilful speaker will derive support, while an unskilful one will only find confusion from the resonance; and the stillness of the place, and its great size, will be tolerably favourable to the attempt. In the choir of a cathedral it is often difficult to distinguish the words of a preacher or reader, and yet it is impossible to help admiring the beauty which the extreme sonority of the place imparts to every musical sound uttered there.

Returning to churches of ordinary dimensions, and of the form generally adopted: the following extract from Mr. Denison,* is interesting, as it practically bears upon this subject: "It is at last discovered," says he, "that, so far from the pillars and aisles and broken roofs of Gothic churches built after the fashion of the old ones being worse for hearing in, they are generally better than the wide spread buildings, all under one span, like a railway station, which it was the fashion to erect in large towns a few years ago. This fact is noticed in two recent reports of the Church Building Society, and I had observed the same thing myself in several instances, even in small churches, though without knowing that it was general, before I read it there. Certainly some of the worst places for hearing in that I know are buildings all under one roof, and of far less capacity than many churches, both old and new, of the nave and aisle construction in which a large congregation can hear perfectly well. So that in this, as in many other things the old Gothic builders knew what they were about a great deal better than we do, who a few years ago despised, and are just now beginning to learn their principles."

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* Lectures on Church Building.

The system of roofs of high pitch with a single span, referred to in the above extract, has been pretty freely employed latterly in the erection of dissenting chapels, but, as might have been expected, with a success far from uniform; for although such an arrangement seems to promise complete freedom from such interruption as arises from *obstacles* to sight and hearing, it is in practice found frequently to result in the erection of places far more difficult to fill with the voice than churches occupying the same area, but arranged in the usual manner with a nave and aisles. The main reason of this misfortune lies in the large amount of empty space which can be dispensed with upon the nave and aisle system, but which would be included under the roof of a building covered in a single span and having the same height. There is another respect also in which the single span building lies at a disadvantage. Even when its roof includes no greater volume of air than that contained in a church of the same area, roofed in the usual maner; its surfaces are much larger, and more unbroken, and its interior is more uninterrupted. If the ceiling has a tendency to cause echo, the more extended the surface the more marked will be the echo. If the air has a tendency to reverberate, the more uninterrupted the mass the less check is there upon that tendency; so that within ordinary limits the practice of exposing the main timbers of church roofs to view is no doubt beneficial, and prevents the interferences that would be perceptible were the church perfectly plain; just as in a large room quite full of scaffolding little or no resonance may be heard, although when the scaffold is removed very decided reverberation may make its appearance.

It is, however, possible to make the forest of timber in an open roof so thick that it may act as a check upon the free passage of sound, and not only is it possible to make the nave unduly lofty, but there is a great temptation to do so on account of the noble effect which such a feature presents. Where a roof of this description is lofty, and of sharp pitch, and is boarded or ceiled along the line of the rafters, there can be little doubt that the meeting of the two sides at the ridge forms a trench that interferes very much with distinct hearing. In a low nave, and with a moderate pitch, this inconvenience may not be felt; but it is rarely absent from a high and steep one ceiled in the manner described. It is far better to cut off the upper angle by a ceiling at the level of the collar, if there be collars, or to form a polygonal ceiling; and it will in all cases, but especially where the church is lofty, be well that this ceiling should be of wood and not of plaster.

The columns themselves, in a church constructed with a nave and aisles, are, it must be admitted, obstacles, and sometimes serious obstacles to the comfort of the occupants of a certain number of seats; accordingly in a few modern churches, and rather more freely in dissenting chapels, architects are learning to avail themselves of the advantages offered by the use of iron, and by diminishing the diameter of the shafts to about six or eight inches, have found it possible to unite the advantages of the ancient form of roof to those of an all but unencumbered area.

Even without the assistance afforded by the use of iron columns, the nave and aisle system will admit, with care, of great extension in length, while enormous structures may be successfully carried out with that assistance.

The architect has greater facilities and even inducements in church building to attend to proportion in his interiors, than in almost any description of work: having ordinarily an open churchyard to build upon, he is, except in cities, not subject to exact limitation as to site, a circumstance which often almost prescribes the dimensions of a building, consequently he may select and may vary his proportions and dimensions at pleasure; the work, too, is of a nature the excellence of which is believed by a large number of able men to depend on a prevalence of definite geometrical proportions in the different parts of the structure; and although we do not frequently employ stone vaulting for the internal covering of our parish churches, a custom to which a large portion of the geometrical relations between the different parts of mediæval plan may be traced, we shall undoubtedly be likely at once to improve the beauty of the structure, and its acoustic qualities, by a careful observance of this harmony between the dimensions of all the parts of the structure, and probably shall do so most successfully as regards sound if, when the nave arches are regularly spaced, the distance from column to column be taken as an unit of measurement; for it is in the highest degree probable that these columns will determine the position of the principal nodal points in the entire mass of air whenever it is set in motion.

The churches built by Wren have been already alluded to; and even those who differ from him in the question of art will not refuse to acknowledge the acoustic success of these structures, and of those built on their model, and will be not unwilling to see the views held by so scientific a man, as they stand embodied in a letter,* already once quoted, which he addressed to a friend, a member of the commission appointed by Queen Anne for erecting 50 new churches in London and Westminster. After referring to statistics which showed the need of the contemplated step, Wren proceeds thus: "If the churches could hold each 2000, it would yet be very short of the necessary supply. The churches, therefore, must be large; but still in our reformed religion it should seem vain to make a parish church larger than that all who are present can both *hear* and *see*. The Romanists, indeed, may make larger churches; it is enough if they hear the murmurs of the Mass and see the elevation of the Host; but ours are to be fitted for auditories. I can hardly think it practicable to make a single room so capacious with pews and galleries as to hold above 2000 persons, and all to hear the service, and both to hear distinctly and see the preacher. I endeavoured to effect this in building the parish church of St. James, Westminster, which I presume is the most capacious, with these qualifications, that hath yet been built; and yet at a solemn time, when the church was much crowded, I could not discern from a gallery that 2000 persons were present. In this church I mention, though very broad, and the middle nave arched up, yet there are no walls of a second order, nor lanterns, nor buttresses, but the whole roof rests upon the pillars, as do also the galleries. I think it may be found beautiful and convenient, and as such the cheapest of any form I could invent.

"Concerning the placing of the pulpit, I shall observe—a moderate voice may be heard 50 feet distant before the preacher, 30 feet on each side, and 20 behind the pulpit;

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* Parentalia, p. 320; Elmes' Life of Wren, p. 430.

and not this unless the pronunciation be distinct and equal, without losing the voice at the last word of the sentence, which is commonly emphatical, and if obscured spoils the whole sense.

"By what I have said it may be thought reasonable that the new church should be at least 60 feet broad, and 90 feet long, besides a chancel at one end, and the belfrey and portico at the other."

Wren's churches * can almost all of them be adduced as affording examples of a disposition favourable to sound, and strictly in accordance with the principles laid down in this short extract; while classic in style, they follow the forms of Gothic churches in plan and section, and it is a decided proof of Wren's preference for a nave and aisles that, notwithstanding his great constructive skill, which gave him every inducement to erect a wide roof, he is not known to have left a single church, except a few of his very smallest, without columns in the interior. In almost all cases he has placed the pulpit some way down the nave, showing that he has depended comparatively little upon assistance from the building; and in all the proportions of the cross section, while they avoid the vice of being cramped, present a certain general impression of lowness in relation to the width. In most of these churches, also, a very large amount of resonant material is employed in the form of panelling to the walls, and in very many galleries are introduced.

The propriety of the introduction of galleries has already been under consideration. Where employed, it will ordinarily be found that they are good places to hear in, because they are necessarily made with seats rising as they recede, and they have commonly a somewhat favourably shaped reflector above them; and because, also, the voice is ordinarily heard better by those above than by those below a

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* Clayton's Churches of Sir Christopher Wren.

speaker. The space under the galleries, especially side galleries, is, however, usually one of the worst parts of a church.

If, therefore, galleries are introduced, the side ones ought to be kept shallow; but the one at the end may be safely made deeper, and if an opportunity offers of carrying it back over a lobby, so as to extend it further than the ground floor below, the seats so gained will ordinarily be found not to be the worst in the church. The front of a gallery ought to be kept as near the level of the ground floor as practicable (9 feet is in most cases ample), and ought itself to be as light and as moderate in depth as possible. Finally, as has been already observed, an end gallery is open to fewer objections than a side one, and has the recommendation that it often prevents an echo from the end wall. So much is this the case that in churches to which extra height is given with a view to the future introduction of a large gallery, and in places of worship with no internal columns, the architect will always do well to introduce an end gallery, even if it be only a very shallow one.

Transepts are of most frequent introduction in buildings built with nave and aisles, and often occur in such examples as would be, even without them, in danger of reverberation from the great loftiness of the nave. They cannot be regarded as usually favourable to sound, though sometimes an architect has succeeded in gaining an additional number of sittings by their introduction, without damaging the excellence of his church. The general fault of them is, that either they absorb all the voice, so that either persons in the nave are unable to hear, or else if the voice is so directed as to reach the nave, they themselves are bad places for hearing in. If introduced at all, transepts are probably best wide and shallow, and it is not unlikely that letting them have a lower roof than the main part of the church, and perhaps even filling them with galleries, will partially counteract their tendency to divide the volume of sound.

The position of a pulpit, reading-desk, or altar, is a point that claims serious attention, because it has been found possible to improve or diminish ease of hearing and speaking in a church to a great extent by a change in the position of the speaker. In different parts of a complete morning service, it is often possible to trace great variation in the ease with which the congregation hear the prayers, the lessons, the commandments, and the sermon. It is a common observation, that in most churches the communion service, read from the altar, is the best heard, although the clergyman is then furthest from the people. It must be admitted that this does not invariably happen, but the frequency of its occurrence seems to point to the influence of the restricted height and width of the chancel, its small body of air, and its parallel walls, as directing the voice well forward in a direction coincident with its natural initial impulse.

The reading-desk and pulpit, in churches, usually stand either in the centre of the centre aisle, or one at each side, and they may be either close to the chancel arch, or pushed far forward into the church.

There are very strong reasons, to be drawn from various considerations of propriety and convenience, why the old-fashioned plan of placing the pulpit in the centre of the aisle, with a reading-desk in front of it, should never be resorted to when it can be avoided. There is an impropriety which all must admit, though by some its force is less felt than by others, in the placing any piece of church furniture between the congregation and the communion; there is an artistic impropriety in constructing a noble central feature and then shutting it out by the pulpit; and there is a great inconvenience to the congregation in having the minister placed directly in front of the east window. To the occupant of the pulpit the position is unsatisfactory, unless the centre of the nave be filled with seats, a custom now abandoned; and the principal thing to be said in defence of it is that if there are deep galleries at the sides, the pulpit fixed centrally will command both of them without being so high as it would otherwise have to be.

A pulpit or a desk fixed at one side of the nave, affords a good view of the whole congregation, and one analogous to that obtained by the speakers at a public meeting, where few, except the chairman, speak from the centre of the room; if there be a tendency to echo, the voice not being directed straight down the church, will fall less fully on the wall at the extremity, and probably will be less distinctly thrown back than when uttered from a central pulpit.

As to the advisability of placing the pulpit forward or back, it depends very much upon the nature of the church. It is usually likely to be unsuccessful to place the pulpit so in front of the pier of the chancel arch, or in front of a wall, that the voice will be liable to be reflected from that wall; a very perceptible confusion of sound accompanies the preacher's voice under such circumstances, and it may be laid down as a general rule that it is always injurious to place a speaker immediately in front of a large dead surface of plaster, or even of stone.

If then the pulpit is near the chancel arch, it should be under, not in front of that arch, and this position will probably answer best in long churches. It is, however, perhaps more frequently advisable to bring the pulpit forward to the distance of say one bay of the nave, and thus let the preacher be to some extent among the people.

A very salutary revolution in the height of pulpits has been effected in practice of late years. In the last century pulpits were made lofty, to suit the high galleries then prevalent—the custom is now to have them low; and it may be fairly advanced as a general rule, that the lowest height that suffices to give the preacher complete command of the faces of the congregation will be found the best, a rule which will render it necessary to raise the floor of the pulpit higher in large than in small churches.

These principles, however, must be advanced with this proviso, that in very "difficult" churches, sometimes an unexpected and almost anomalous result is gained by experiment; and in a case where it is sought to improve the speaking in such a church, the wisest plan is to put up a temporary pulpit, capable of being tried in different positions, and with a floor that can be raised or lowered at pleasure. Instances have occurred where the centre of the centre aisle proved decidedly the least bad situation (this may be anticipated as possible when a church with transepts proves unsuccessful), and where defects, at least the defect of echo, became less apparent when the pulpit has been raised, but these are exceptions to the ordinary course of things.

The injury to the comfort, health, perhaps life, of a clergyman compelled to do duty in what is called a difficult church is so grievous, and the annoyance to the congregation so great, that no means should be left untried to correct defects where they have shown themselves.

In cases where the congregation hear better from the altar than the pulpit, it sometimes will answer to put the pulpit in the chancel, and where there are transepts, and a difficulty is felt in filling the nave, a point in the chancel may sometimes be found, where just so much assistance is given by the chancel walls as to send the voice down the nave, without cutting it off entirely from the transepts.

For reverberation, the use of drapery in the roof is often the only resource, but this has so unsuitable an appearance, that before having resort to it, every possible application of a sounding-board should be tried. It is of course undesirable to have recourse to this or any other auxiliary, but as palliatives and remedies sounding-boards or other reflectors are no doubt among the most valuable we can command, and considering how simply a temporary sounding-board can be made, and how easily it can be fixed, this is probably the first expedient that ought to be tried in any attempt to improve the speaking in a difficult church, more especially if there seems reason to believe that an excess of space around and above the speaker occasions the defects, by swallowing up the sound.

It would be advisable in making such a trial to take some trouble to secure that the wood employed should be cut thin, thoroughly well seasoned, and fixed in as few pieces as possible. The sounding-board ought to be a large one, and experiments had better be made to determine the best height and position for it. If hung horizontally, it will be most likely to be of use if placed well over the speaker, but if allowed to drop a little at the back, so as to be somewhat inclined, a position in which its efficiency will be likely to be increased, the sounding-board may then be safely kept further back.

What has been already said about reflectors * may assist the architect to form some idea whether the concave reflector of Mr. Blackburn, or the convex reflector of Mr. Penrose, would be worth trying in any building which he may be endeavouring to improve. Sometimes, especially if there be reason to presume that the east wall of a chancel returns an echo, an upright screen of wood behind, with or without any reflector above the pulpit, will prove advantageous. Whatever plan is adopted, it ought to be remembered as an invariable rule, that no sounding-board, or wall, or reflector of any sort, ought to be quite close to the speaker.

It certainly comes within the province of any work treating, however incidentally, upon the arrangements of a church as regards sound, to notice the position of and provisions for an organ. The essential precautions to be taken with regard to an organ are summed up by Mr. Blomfield † as follows :—" An organ, the most beautiful of instruments when in tune, is one of the most disagreeable when neglected,

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* Ante, pp. 61-69.

† Paper on Church Arrangement, read before Architectural Association, Dec., 1860. See *Builder*.

and every one should know how sensitive it is to damp and draughts, in order to guard against this in his arrangements for the reception of the instrument. If there is a choir, the organ should always be placed close to them, and the proper place for it is either in a side aisle of the chancel or in an organ chamber built expressly for it, which is better. The effect of the instrument will be much enhanced, and it will be kept in better tune, if the walls are lined with boarding on battens; and if not in a gallery, it should always be raised on a platform some feet from the floor. The worst place for the organ on every account is the west gallery, if there is one, and I believe organs are never now placed there in new churches." It may, however, be right to add the suggestion, that if the architect has no control over the purchase of the organ, and has reason to know that the organ being built for any church is twice as powerful as it ought to be in proportion to the size of the building, as not infrequently occurs, it will be wise to consider whether the west gallery may not be under the circumstances the most appropriate position for it.

Places of public worship built without a nave and aisles do not differ very materially from public halls, except in the nature of their fittings; they have been adopted more or less commonly by all denominations, and though no exact rule has been followed, yet, generally speaking, it may be said that most churches and chapels for the use of the Church of England and of Roman Catholics are built with a nave and aisles, while churches and chapels for other religious bodies are generally built without this arrangement.

The large unbroken surfaces and great internal capacity render it a matter of difficulty to secure the success of a large chapel, precisely in the same way and nearly to the same extent as they will be shown to militate against the success of large halls. The power of fixing the exact position of the speaker, and the opportunities for introducing features for which a mere public room affords no scope, are, however, in favour of the architect engaged in chapel building.

The old-fashioned build for dissenting chapels and for churches, in which flat and low ceilings were common, produced very many places of large size, which, on account of this very lowness, are extremely easy to fill with the voice. A large chapel, and of lofty proportions, even with a flat ceiling, is often very formidable to the speaker; and those buildings where a tolerably high-pitched, wide roof, open to the ridge and in a single span, is adopted, are in the majority of instances very difficult to fill, and very liable to reverberation and echo. A chapel or church of this sort is best ceiled with wood, or plastered between rafters, and ought always to have its ceiling only moderately high, and either flat, arched, or running along the collars of the roof, and the precautions which will be referred to under the head of large rooms, ought all to be observed whenever the building partakes more of the features of a hall than of those of a church, whether it be simply a hall, or be a place of worship.

To such a building the introduction of galleries will ordinarily be an advantage, unless the side galleries be disproportionately deep; and an end gallery, together with the columns supporting it, and some sort of recess at the back of it, can often be made useful to cut off echo. An organ gallery is a feature frequently introduced with advantage—if no other gallery be needed—and is sometimes placed behind the pulpit in chapels in a recess, where it seems to act favourably upon the preacher's voice, its front forming a kind of resonant screen behind him. Such a screen may also be used with benefit when there is no organ.

In churches where there is a chancel, what has been already said about placing the pulpit holds good. In chapels it is usually considered essential to place the pulpit in the centre of the end of the building, though it is open to doubt whether it might not sometimes prove advantageous to move it to one side, when circumstances will justify that position being preferred. It will in no case be advisable to place it quite close to a wall, and it would in square chapels, or those approaching squareness, be no doubt advisable to place it further forward amomg the congregation than is customary.

A recess is commonly introduced in chapels behind the pulpit. Beyond furnishing a feature, this recess no doubt is valuable on account of its removing the wall surface some distance away from the speaker, without its being necessary to throw the pulpit far forward. As the communion table and an appropriate space round it are in a majority of chapels for dissenters always in front of the pulpit, this recess affords an arrangement not far removed from that of the earliest basilicas; perhaps in some instances this resemblance might be increased, and the suggestions just made combined, by bringing the pulpit forward on one side of the communion, after the manner of an ancient ambo, and placing a suitable seat in the position it had occupied.

In Scotch Presbyterian churches the favourite position for the pulpit is against the centre of one of the longer sides of the building; but this position seems one of the worst that could be chosen, because it places the fewest auditors in front of the preacher, when his voice would naturally travel farthest, and greater numbers at the sides, where he can only be heard indirectly; and it exposes a large number of persons to the danger of losing the words of the preacher should he turn towards his right hand or his left, and introduces the necessity of seating the congregation so that if they all look towards the pulpit, they must some of them look towards each other.

For a moderate sized place of worship, however, this arrangement has the advantage that it places the preacher uniformly near to every part of his church, much more so than he would be if at one end of it, and that perhaps it lessens the risk of annoyance to the congregation from echo; but for large churches, it seems to be a disposition very unlikely to prove favourable to the comfort of either preacher or hearers.

Buildings for public worship on a circular, octagonal, or other plan, are from time to time erected, but it must manifestly be difficult, if not impossible, to offer any suggestions that will be generally applicable to them. Ordinarily, peculiarities of site have led to the adoption of these plans, and probably the most successful treatment for such cases will be one which abandons the attempt to preserve most of the ordinary conventionalities of church arrangement, and facing the exceptional difficulties presented by the circumstances, produces a good common-sense building,* the main defect of which will be likely to be that its appearance will not probably suggest adaptation to the purpose for which it was erected, but to a different and perhaps an opposite one. Where a form of this nature is selected on preference, this objection will most likely not be felt serious, and the observations upon the class of buildings built in dependence upon natural radiation of sound will, some of them, be found applicable.

Buildings for religious purposes roofed in a single span form an appropriate link between churches with nave and aisles and public halls, allied as they are to the one by their form and to the other by their destination. If more has not been here said about them, it is chiefly because what else remained to be remarked seemed placed more appropriately under one or other of these related heads, and we pass on therefore to modern public rooms and halls.

In the majority of modern buildings for secular purposes, the circular or semicircular form of the ancient Greek theatre, and the columnar arrangement of the basilica or church, have been both rejected, and an oblong hall preferred. That this is the best form for general purposes admits of great doubt, but it is a form so much sanctioned by usage that it cannot fail to be constantly in request, in every variety of size and style, and for every possible purpose.

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* *E.g.*, the chapel formed out of the old Diorama, in the Regent's Park, or St. Mary's Church at Hastings, or Surrey Chapel in Blackfriars-bridge Road.

Although the construction of a hall large enough to accommodate a very vast auditory, is more conspicuous as a difficult architectural achievement than the erection of a moderate-sized public room, and the responsibility of undertaking to design a very large hall that shall prove when built thoroughly suited to public speaking, becomes grave on account of the formidable magnitude of the failure should a failure occur, it may be doubted whether there really is so much risk of non-success in buildings for five thousand auditors as in those for five hundred. The great dimensions of a large hall remove the walls, from which echo is likely to rise, too far from the speaker's position for his voice to retain its full power when it reaches them; consequently, if an echo is heard, it is but a feeble one. Structural difficulties and general principles of convenience, not to say considerations of economy, ordinarily combine to prevent unduly lofty proportions in such vast rooms, while as such places are ordinarily built by those who have sufficient funds at command for some degree of internal architectural display, there is opportunity both for modifications of general form and enrichments of surface, such as are likely to prove acoustically advantageous. Still the successful construction of a very large hall, in which a far larger number of persons can hear than could be addressed in the open air under ordinary conditions, will always remain an honourable achievement; and whatever the difficulties of smaller buildings, it will always remain a disgrace that rooms should be built not large enough to hold more than the half or two-thirds of an out-of-doors audience, but in which (notwithstanding their moderate dimensions) no speaker can use his voice with ease, and many of the listeners can only hear indifferently.

It may without much danger be advanced that the plainest and most simple form of public room—namely, one rectangular in plan and in section, presenting consequently straight walls, a flat floor, and a flat ceiling, and having all the junctions of ceiling with walls or walls with one another at right angles—is of all others the form most liable to acoustic defects, and that in proportion as this type is improved upon the chances of success are increased. The flat floor of such a room renders it liable to the obstruction of direct lines of sight and hearing, its flat sides and square angles are apt to favour the generation and reflection of a conducted wave of broken sound, and to promote reverberation. Its flat ends are liable to cause echo; and the equal height throughout furnishes a mass of air above and behind the speaker which may be injurious; the windows or skylights, if they partake of the general squareness, will each have its own little cube of sonorous air ready to be set in vibration, and to create in this way a disturbing sound, while the uninterrupted openness of the whole space aggravates the evil by allowing every echo and every reverberation, once roused, the fullest scope to continue as long as it can without check of any sort.

It will be readily perceived that the introduction of architectural features of almost any description will tend to lessen some of the disadvantages spoken of above. The formation of a recess for the orchestra or platform at one end, and masking, breaking up or curving the opposite end, ornamenting the walls or ceiling or both to a moderate extent, rounding or canting off the angles, bringing the ceiling on to the walls with a cove or a cant, and breaking it up either with groining or by means of some sort of open roof (but not with deep square coffers), are all not only methods of adding architectural effect, but of avoiding the risk of acoustic failure.

Some of these methods, especially the canted ceiling and partially open roof, are generally applicable to even the most economical of structures; but sometimes, as for instance in large schools, where there are rooms built over one another, it will be necessary to build rooms of large size perfectly plain and rectangular. Of the safeguards which in that case can be suggested, the first, and by far the most important, is the avoidance of anything like lofty proportions; in addition to which it will also be well to avoid, as far as possible, plastered surfaces and deep recesses for doors, windows, and skylights, and to endeavour to secure some simple numerical proportion between the different dimensions of the room. If to these obvious expedients can be added a use of resonant materials near the speaker, in the shape of wooden linings, and perhaps some curtains or other drapery in the remote parts of the room, where echo would be likely to rise, nearly as much will have been done as is possible in cases where very limited means only are available.

The defect in these very plain halls is always of the kind resulting from excessive sonority taking the shape of echo or of reverberation, and consequently the best palliatives in bad cases, which it is desired to cure, are curtains, matting, and other non-reflecting substances, and altering the relative position of speaker and hearers.

If now, advancing one or two steps, we turn to public rooms of small size and moderate pretensions, such as are to be found in the lecture rooms of scientific or literary societies, and the town halls or lecture halls of many provincial towns, we find a knowledge of the laws of sound needed in the adaptation of them to their purpose. Large school-rooms, lecture halls, assembly rooms, and, in fact, the majority of halls of moderate size are very liable to acoustic defects. One great cause of these is the disproportion that rooms of this class often exhibit; another, the empty bareness and flatness which they often share with rooms of the most rudimentary class; and a third, and very obvious one, is the short distance which the voice travels before it meets the wall or other surface by which, if there is an echo, that echo is occasioned. It must not be supposed that it is necessary, in order that echo may be raised, for a room to be even fifty or sixty feet long, so that the echo might be returned at an appreciable distance of time after the original sound. In apartments of very moderate size echo may be quite perceptible, and such echo as follows instantaneously upon the utterance of a word is hardly less confusing or annoying—as has already been noted in considering the position of a pulpit—than that which is heard after a short interval; while, of course, the nearer the reflector to the source of sound, the louder the reflected sound will be.

It would be of advantage to this class of building if piers, when they are used to support the roof trusses, were brought inside instead of being added outside the walls, if the common plastered lining were abandoned in favour of well-executed brickwork, or a match-boarded lining, and if more care were taken about proportion. Where practicable, it will be preferable to employ windows rather than skylights, and if skylights are employed they ought to be nearly or quite flush with the general ceiling. A wooden ceiling, or at least one ceiled between the rafters, is preferable to a plain plastered one; and the same precautions as to shape of ceiling, &c., advised for adoption in arranging the simplest rooms, will be equally desirable in somewhat better ones. A cove at the sides of the ceiling may often be introduced with advantage, and if it be large so much the better. This feature not only cuts off one of the objectionable series of angles, or more properly angular channels in a building, but affords an opportunity for masking low proportions by the apparent increase of height that it imparts. If there is an open roof, or, what is better, one partly open and ceiled at the collar, the timbers ought not to be very meagre and far apart, that is if it is wished that they shall at all check reverberation. The formation of a sort of recess at one end, and the introduction of a gallery across the other, are measures well adapted to the usual purposes for which these rooms are wanted, and very likely to be conducive to their success as regards acoustic qualities.

It is to be wished that a larger proportion of the entire expenditure were devoted to the *interior* of rooms of this class, than is at present allotted. Care and skill can sometimes secure the excellence of such rooms without additional expense, but where the formation of such features as are here advised would increase the cost, it would always be wise to encounter that increase, even at the risk of sacrificing external effect, since the object of the erection of a public room is entirely defeated if, when built, it proves unfit for public purposes.

Of public rooms which have proved defective for sound probably the best examples are those built for corn exchanges; and here it may be remarked that in a building intended for use as an exchange only, it will be desirable rather than not to encourage reverberation, as the occupants will all prefer that the sound of their voices shall be audible no further than to the person they are addressing. Square plan, lofty proportions, bare plastered walls, square recesses, deep skylights, and a hollow space under the floor, which should be of wood and not carpeted, will in such a case be adopted and not avoided.

In attempting to remedy defects in large rooms, the methods to be followed must depend of course on the nature of the defect observed, and on the judgment of the architect as to its cause. It is worth consideration among other remedial measures, whether, in some cases of excessive height, raising the floor some feet might not be as efficacious as any plan for reducing height by altering the ceiling, and more easily tried. The introduction of non-reflective materials, and the cutting off vacant spaces, have already been suggested, and in cases where space over the speaker or musicians seems too great, the introduction of a large sounding-board, hung so as to incline slightly upwards, will be very likely to be of service. Where reverberation is apparent in the upper part of the room, hanging flags or other draperies at intervals seems very often to check it. Sometimes a great improvement can be made in a room by simply altering the level of the platform from which persons speak, which very frequently is too high, and in building new rooms it will always be well to let this platform be low, and, where circumstances admit, to let the back of it rise in steps, like an orchestra.

If in the largest and most highly finished public rooms there is more opportunity for introducing architectural features, less risk of disproportionate height, and less chance of violent echo, than in rooms of moderate size, it must not› on the other hand, be overlooked that the wall spaces and ceiling in very large rooms are so great, and the contained mass of air so large in volume, that what in a small room might be only an insignificant mistake, would in a large hall occasion formidable obstacles. The comparative feebleness of the echo roused by a speaking voice, supposing any echo to exist, will not secure immunity from violent interferences if the hall be used, as all halls now are, for concerted music; and the immense difficulty of introducing remedies on a sufficient scale to counteract any imperfection once suffered to appear, will always render the acoustic success of a large hall a matter of such anxiety that it is a happy thing to have reason for believing that immense size really does remove some portion of the obstacles which beset small rooms.

It seems extremely probable that halls of great magnitude and great beauty might be built on the general plan of an ancient theatre. The chief modern instance that presents itself to our notice is the Handel Orchestra at the Crystal Palace, a structure not originally intended for auditors but for performers; but which would be so manifestly appropriate for a large audience that it may be fairly hoped to lead to the adoption of this arrangement in other buildings.

Great halls, however, as now understood, are either adaptations of the ancient Roman halls which formed the central features of their baths, or enlargements and improvements of the modern European oblong rectangular room. The former follow a type that was never intended for an auditory, and are not ordinarily so well adapted for public speaking as for purposes of assembly and display; the latter, built exclusively for music and speaking, are of comparatively modern growth, their prototypes being no doubt the great halls of mediæval times, and the large churches without internal columns of the preaching orders of friars.

A comparison of a few successful halls will show very great variety to exist in many characteristics, but a general agreement in the essential points that characterise a building adapted to direct and preserve from decay the sounds produced at one end of it. The ceiling may be curved or sloped in various ways, but it is never in good examples horizontal throughout.* Various modes of restricting the space near the speaker are adopted, but some such diminution is always to be noticed. The methods of counteracting echo may vary, but in all cases some safeguard will be adopted, and though the sections of different buildings will differ extremely, they will agree in presenting a moderate average of height in proportion to the width.

One of the best examples that can be presented of a successful public room of the largest size, is the Free Trade Hall at Manchester, rebuilt by Mr. Walters, and shown by the accompanying illustrations, Nos. 15, 16, and 20.

The requirements here, as in most great rooms, embraced fitness for both musical performances and public speaking, with accommodation for a very large audience, solidity of construction, and good architectural effect, and they have all been met successfully.

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* The ceiling of Exeter Hall, which was originally horizontal, has been, as is well known, altered, and now presents a flat pointed arch in section. Considerable benefit to the properties of the hall has followed the change.

The dimensions * of the great hall are very considerable; its height is 52 feet, its width 78 feet, and its length to the back of the recess for the orchestra 135 feet, or, exclusive of that recess, 123 feet; so that the height bears exactly to the width, and approximately to the length, the simple numerical relation of 2 to 3 and 2 to 5, the unit being 26 feet.

The plan is a parallelogram, with a recess for the orchestra at one end, and a semicircular sweep in place of a straight wall at the other. The ceiling, as the cross section shows, is panelled, and joins the walls by a very large cove, which is slightly broken into by a series of intersecting arches, and not merely is the space at the sides of the orchestra diminished by a recess, but the ceiling is also brought down over it. The floor of the main hall is inclined slightly at the back, the rise being about two feet, and the incline commencing at about one-third of the length of the hall from the platform.

There is one gallery occupying both the end and the sides. The side walls are plain below the gallery, the upper part of them being only broken by engaged three-quarter columns, carrying arches, so that they offer no obstruction to undulations that might pass them, though the formation of an accumulated wave of conducted sound (as in a whispering gallery) will be prevented. At the remote end of the building (whence echo would arise if it existed at all) every means has been taken, in addition to the semicircular form given to the walls, to break up the surfaces. Under the gallery, large entrance doors, covered with cloth, are introduced. The gallery itself becomes deeper at the end than it is at the sides, so as more effectually to check the sound that might reach the back wall and be echoed.

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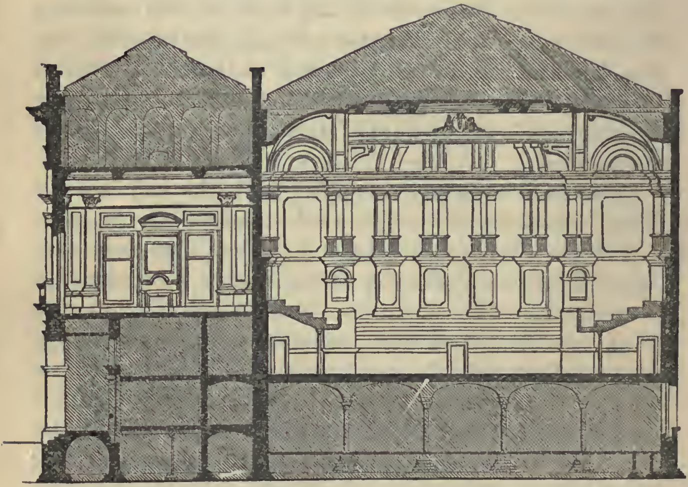
* *Builder*, Sept. 1856.

Above the corridor shown on the plan a series of private boxes are formed, the three-quarter columns becoming here detached, with open spaces between them, and balconies on bold corbels being thrown forward to occupy the interspaces. The section of front of the gallery is a curve of compound flexure, so that it cannot echo, and the cove of the ceiling runs round the sweep. This room, when empty, possesses a good deal of sonority, but when full is excellent in the extreme, either for music or public speaking.

The amount of resonant material employed is not great, although there is a good deal about the orchestra, the part of the building where it will be of most service. Considerable resonance is, however, procured by the large space above the ceiling and by the fact that there is a hollow space under the floor; the included mass of air is probably also nearly as large as could be safely set in motion, so that in all probability the architect of this hall may be considered



TRANSVERSE SECTION

Fig. 15 —Free Trade Hall.

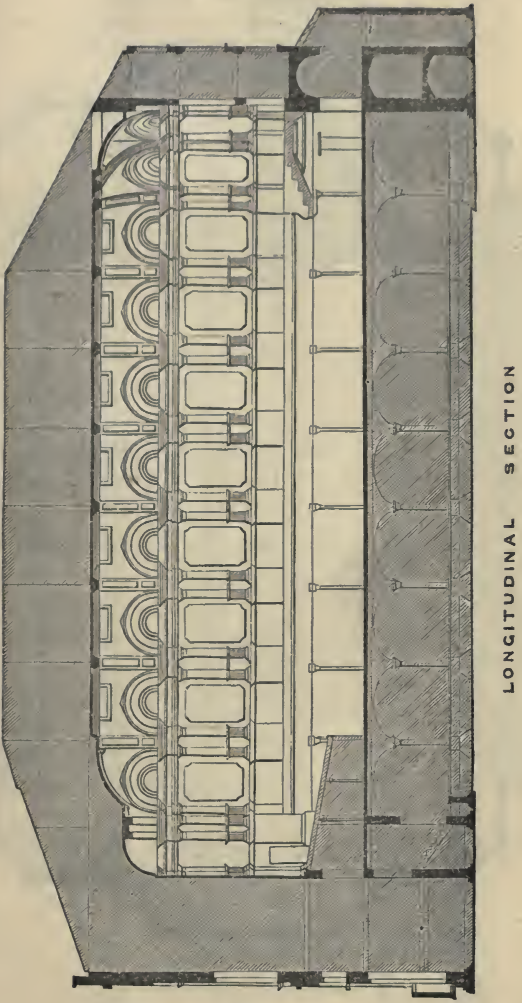


Fig. 16 —Free Trade Hall.

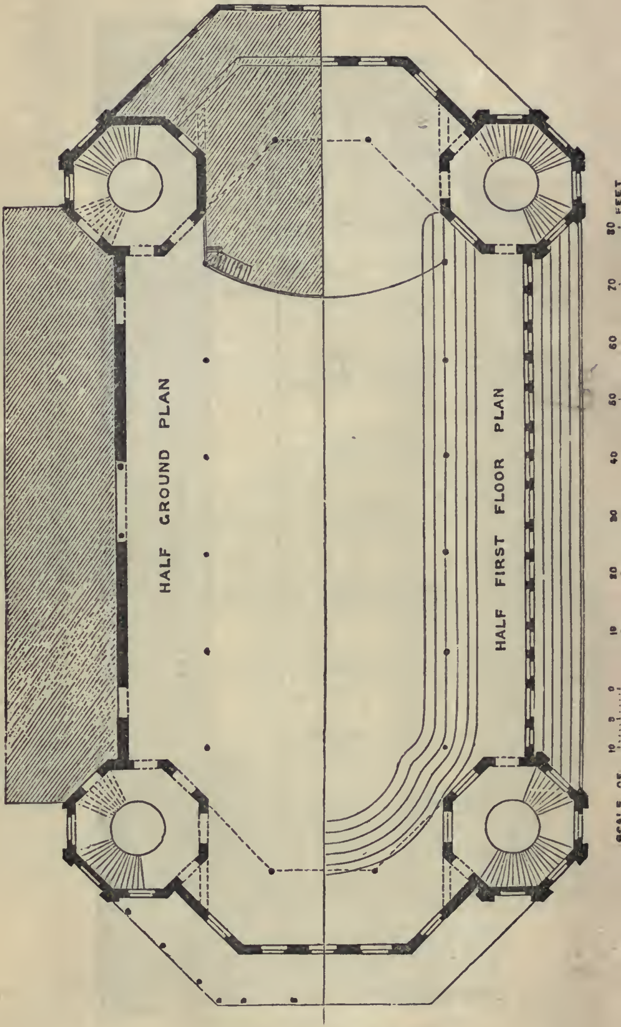


Fig. 17 —Surrey Music Hall.

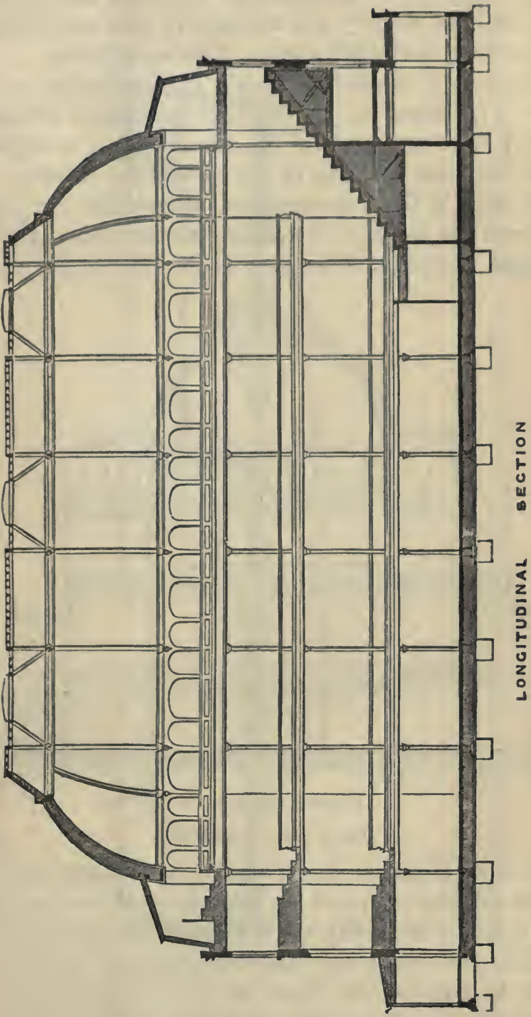


Fig. 13 —Surrey Music Hall.

to have approached as closely as was either salutary or safe that limit of capacity and sonority, to have exceeded which would have spoiled the success of his undertaking.

The Surrey Music Hall, shown in the illustrations numbered 17, 18, and 19, is a very good example of a successful hall of large size; most of the peculiarities of which offer a wide contrast to those of the last-named building. We have here a light construction, surrounded by tiers of galleries one over the other, having a lofty roof on a series of internal columns, and the floor on the level of the grounds with which it communicates directly by its many doors, just as the galleries open into the balconies that surround them. The points of similarity are the general disposition of the building (an oblong with the orchestra at one end), the care taken to give suitable forms to the end of the hall, the section of the roof, the front of the galleries, &c., the recess for the orchestra, the good proportions, the restricted mass

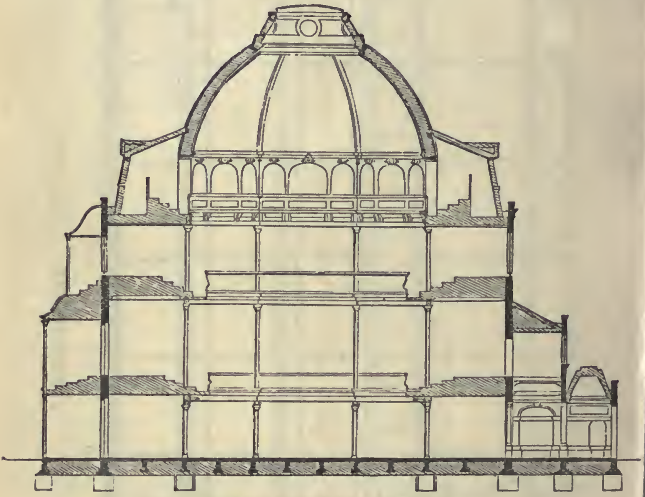


Fig. 19.—Surrey Music Hall.

of air in the building, the careful avoidance of echo, and the judicious employment of resonance to support the voice or instruments.

The general form of this hall may be described as an elongated octagon or a parallelogram, with semi-octagonal ends, into which the walls of the staircases project, so as to convert them into recesses.

There are three tiers of galleries, supported on light iron columns, and with fronts of curved section. The ceiling over the central space is of domical section, and that over the galleries inclined.

The very steep rise of the orchestra cuts off a great deal of vacant space behind the performers, and the roof comes down over them; but in order further to restrict the space, a large sounding board, not shown in our illustration, and made of old well-seasoned wood, was hung over the orchestra. The forms, it will be seen at a glance, are well chosen throughout the building, and the proportions are also good. The extreme length is 163 feet 6 inches, the width 68 feet 6 inches, and the height to the underside of the ribs of the ceiling is the same; so that the width is to the height and to the length as 1 to 1 and 1 to 2½. The main reliance of the architect was, however, on the use of resonant materials, and these were employed freely. Beside the wood work of the galleries and orchestra, and the wooden sounding board, the whole walls were lined with boarding on battens, with a special view to promote resonance, and the ceilings, which are plastered, were originally intended to be of wood, for the same purpose. The success of this hall both for music and public speaking was complete. Very large audiences, which have been differently stated, but cannot be estimated at fewer than 8000 people, and probably much over that number have been able to hear perfectly in even the remotest parts of the building; and vast as it is, even professional musicians consider it one of the best music-rooms, large or small, in the metropolis.

The "Metropolitan Tabernacle" of Mr. Spurgeon is of too recent erection to be fairly available as an example of a well known and thoroughly tested acoustic building, but it promises to prove successful, and on examination will be found to possess a great many of the peculiarities of the Surrey Music Hall, and to depend mainly upon similar arrangements of form and a similar employment of resonant material for its effect on sound.

The new room erected in Edinburgh by Professor Donaldson, conspicuous as having been built according to carefully regulated harmonic proportions, has been spoken of by those who have visited it as remarkably successful for music. This room measures 36 feet in width, 48 feet in height, and 90 feet in length, and the relation between these dimensions is founded upon the simple but intimate relation between the numbers 3, 4, and 5, a relation which may be illustrated by remembering that if a right-angled triangle be described, having the two sides adjacent to the right angle respectively 3 and 4 units long, the hypothenuse will be 5 units in length. Twelve feet has been selected as the unit, and the breadth of the room has been made three twelves (or 36 feet), and the height four twelves (or 48 feet). Five twelves (or 60 feet), however, which would follow from the simplest application of the harmonic numbers, has been extended to seven-and-a-half twelves (or 90 feet), for the length of the room, by adding to the original dimension its first harmonic subdivision—its half. We are not informed what the natural note of this room is, but it seems reasonable to presume that it must be that due to an undulation 12 feet long, or to one the length of which is some multiple or submultiple of 12 feet. "The position of the windows, height and dimension of the cornices, &c., &c., have all been regulated by these harmonic numbers, 3, 4, 5."

It is not to be understood that these proportions are adopted in this instance as the only good ones, nor is it wished by the learned designer of this room that it should be considered a model music-hall for all purposes, and under all circumstances. In fact, the great height in proportion to the width would clearly become prejudicial were all the dimensions doubled. This room is rather to be regarded as one of the best illustrations existing of the importance, especially for music, of definite harmonic proportions, and as elucidating, though not authoritatively fixing, the mode in which such proportions may be regulated.

It has appeared sufficient for purposes of illustration to bring forward only a few examples, and those of well-known and generally accessible structures. Most readers will find opportunities of verifying the views laid down by other examples of public buildings, especially of places of worship, which last seemed too numerous for it to be quite fair to select one or two single instances for either praise or blame.

It now remains to make one or two observations on smaller rooms, such as committee-rooms and board-rooms, private chapels, or music-rooms in private houses, and even ordinary dwelling or reception-rooms, all of which are liable to acoustic defects and capable of acoustic excellence, notwithstanding their moderate size. It often happens in public institutions containing one large room (for example, a board-room), that in defiance of architectural proportion, the smaller rooms on the same floor are built of the same height, though not perhaps one-third the width of the large one. Such rooms are usually bad for speaking and hearing in, and it is not to be wondered at that they should be so. Cubical rooms, *i. e.*, such as have nearly the same dimension each way, are, as well as over-lofty ones, all ordinarily bad, even if quite small, and should be avoided. Circular and octagonal forms, and breaks or recesses where they can be introduced, are always, on the other hand, to be recommended, as likely to diminish the liability to disturbance in any moderate-sized apartment.

In a room specially intended for a music-room, or for a public business-room, the architect will do well to adopt a ceiling not perfectly flat, and, if possible, of wood. It may also be serviceable to introduce wood as a lining to the walls, even if it is to be covered with paper, and it will be well in such a room to discourage the introduction of a large amount of furniture; and if there are window-curtains in a music-room, it will be better for them to be kept entirely within the window-reveals. Such a room would be an appropriate place for the introduction of ornamental wooden flooring, such as might induce the occupiers to dispense partially or entirely with carpets.

In board-rooms, however, and other public rooms, the advantage of a carpet to deaden sounds of feet upon the floor, and other disturbances, will more than counterbalance any loss of sonority that may be experienced. Board-rooms may often be appropriately panelled with wood. This was done by Mr. Hardwick at the board-room at Euston Square Station, a room in which the slightest sound is distinctly heard.

Among expedients recommended by some authorities, may be mentioned the precaution that all wood, whether in floor, ceiling, or linings to walls, shall be not only well seasoned, but in as long lengths as can be procured. There seems some probability of advantage from this; at any rate, there can be no possible detriment to a room from using long lengths of timber within the room itself, but harm may sometimes result from allowing joists or girders to run through a partition, so that one unbroken piece of timber lies under the floors of two adjoining rooms. A single girder has been known in this way to convey sound from one side of a seemingly impenetrable wall to the other, in a manner apparently most mysterious, till accounted for by the accidental discovery of the piece of timber.

Under the title of "Miscellaneous," we must consider some few structures which cannot fairly be classed under any of the heads that have been successively considered, but which have a claim to be at least mentioned in any treatise on the Acoustics of Public Buildings. The most prominent in this miscellaneous class is the Crystal Palace.

Although so much music has been performed in the Palace, opinions are very much divided as to its suitability for the purpose. It seems pretty clear that no echo, or but very little, is experienced from the glazed surfaces, and it will probably not be far from the truth if we say that nearly all the advantages obtained by performances in the open part of the Palace are shelter, a quiet atmosphere, and the absence of echo. Probably the influence of the vast mass of wood in the Handel Orchestra, and some amount of benefit from the enclosure behind it and the velarium which covers it, must also be taken into account when the performances are on a great scale. The concert-room of the Palace, a large temporary hall, has on the whole well-arranged forms, though perhaps too bare and unbroken, but it cannot be called a favourable room for music, and its want of sonority is probably a consequence of the fact that it is not lined with wood or other resonant substance, or even with hard, non-resonant material, but with canvas. The experiment of musical performances in the Floral Hall, as well as at the Crystal Palace, while demonstrating the possibility of sheltering a vast audience, which, when grouped round a full orchestra or a singer with a powerful voice, shall be able to hear music in a manner satisfactory to itself, seems to add an additional proof, if one were needed, that glass structures are not adapted to act favourably on sound.

All temporary erections of canvas, tents, awnings, and marquees are very deadening in their effect on the voice; and on any great occasion, when it is necessary that speeches should be made under such shelter, it will be quite worth while to form a rough sort of recess of boards, or, at least, to make a temporary wooden screen, having something like a sounding-board connected with it, in front of which the speakers could stand.

Whispering-galleries, and places where a low sound is transmitted to a great distance, have always been objects of much and not unnatural wonder. Some of them depend upon the conduction of the sound along a very smooth surface, and others upon its reflection; but in either case the surprising loudness with which a whisper uttered at the proper place is heard at some other spot, is due to the coincidence at the hearing point of several rays of sound reaching it at the same time by different paths. Thus we have seen that in the whispering-gallery at St. Paul's the sound reaches the point where it becomes audible by two different paths of equal length, so that a double effect is produced on the hearer. St. Paul's is an instance of conduction along the walls; in other cases, as, for example, in the celebrated one at Girgenti, we have the phenomena of concentrated reflections, the action of which can be easily shown by fixing two circular reflectors of parabolic form facing one another, but at a great distance apart,—a faint whisper made at the focus of one will be heard concentrated at the focus of the other, nearly as loud, though not so distinct, as if the listener were close to the speaker.

In this case all the rays of sound which fall upon the first reflector are thrown by it to the second, which concentrates them, and it will easily be understood that an ear at any point midway would intercept only a very small portion of the passing sound, probably not enough to make any audible impression.

Where sounds are emitted under a smooth hollow vault of a conical shape they will be no doubt concentrated towards the apex of it. This is the case in the common hearing trumpet, and occurred in the famous prison at Syracuse, called the Ear of Dionysius, which was, in fact, nothing else than a hearing trumpet on a great scale. Such constructions are not now needed but the arrangements of modern prison discipline have rendered an exactly opposite character in prison cells a desideratum, and one of the problems of the present day has been how to isolate these cells, so as to prevent the possibility of the prisoner confined in one cell being able to communicate with the occupant of an adjoining one.

An ingenious method of preventing oral communication through air-flues in prisons has been already referred to. The construction of cell walls in such a manner as to render them sound proof has been the subject of experiments described in some of the Government reports, and in the masterly report on prison construction and arrangement presented to the French Government by M. De Metz; the general result arrived at being that double walls, with the hollow filled with sand, were found more impenetrable to sound than any solid construction.

The general principle of weakening the impulse by repeated checks is applicable to the windows of rooms adjoining public thoroughfares, so as to prevent disturbance from noise outside. The usual and the best precaution is to have double sashes to such windows, but it would be a saving of expense, and probably quite as effectual a plan, so to arrange a single sash and frame that two panes of glass, with a small space if only half an inch between them, might be fixed in it. Even a very light curtain will intercept a good deal of sound, but two or three curtains form as effectual a barrier as a stone wall, especially if they are heavy ones.

Bells, organs, and orchestras are so intimately connected with architectural acoustics that they ought not to be passed by without mention; the two latter have, however, been casually touched upon, and it only seems necessary to add here that in building an orchestra care should be taken to use the best seasoned, oldest, driest wood possible, which had better be employed in long lengths. It will be prudent to leave under a raised orchestra, and especially under the front of it, vacant spaces, which had better be entirely unoccupied, the front of which, next the room, not being exposed to much wear and tear, may be well made of extremely thin boarding. It seems, too, desirable that the incline of the seats should be on an isacoustic curve, becoming very steep at the back.

Beyond the few remarks on the position of an organ, already introduced, it would be difficult to consider that instrument at length without importing into this volume matter foreign to its purpose.

Fortunately also it will be unnecessary to add any explanations with respect to bells; all that could be advanced here about them will be found better said in Mr. Denison's treatise,* and in the other publications mentioned in connection with it in the list of books of reference at the end of this volume.

The application to practice of the principles and laws of acoustics will not only have reference to the arrangement of new structures, but to the endeavour to remedy the *defects* of existing buildings; and here the first step of course will be to verify the existence, nature, and extent of those defects.

In forming an opinion upon the success or failure of any public room or building, by far the surest guide is the account given of it by the persons who speak or sing in it. Out of a large audience, even in a defective room, there may be many, perhaps a large proportion, who will hear well; and in conversation with frequenters of any such place, especially if it be a place of worship, where the same persons occupy the same seats on every occasion, the architect is quite as likely to hear the opinion of those who, occupying the best seats, are able to hear with perfect comfort, as that of those who, occupying remote seats, feel inconvenience. Again, in many buildings radically defective, but not so to a great extent, it is possible for a speaker or singer to make himself heard to the remotest corner, but at the expense of an undue amount of exertion, or a troublesome management of the voice. Of this fact the frequenters of the place may never be apprised till they learn it from the failure of the voice of the accustomed preacher or speaker, or from their inability to hear the words of some stranger with only moderate vocal powers or skill. Lastly, in the case of music, the writer is convinced that comparatively few persons are alive to the difference between a good music-room and a bad one; and though to a delicate or well-trained ear half the pleasure of music is lost if performed in a noisy or a deadening dull room, it is ten to one if a casual auditor would complain of any defect in the room, though he might be quite alive to the fact that the same performance had given him more pleasure on some other occasion—a circumstance which he would probably unjustly attribute to some variation in the manner of the performer.

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* Rudimentary Series, No. 67, 68.

None of these sources of error are liable to mislead a preacher, speaker, singer, or actor, when exercising his voice. He feels at once whether he is filling the building with his voice and whether he is doing so with ease or effort; if he be a musician, he is quite conscious of support to the tones of the voice in a good room, and opposition to it in a bad one; and if the room be in other respects good, but too vast, he may perhaps be unable at first to detect any difficulty in speaking, but will complain of undue exhaustion in consequence of being insensibly induced to exert himself over much. When a speaker feels difficulty in speaking it is *certain* that some at least of his hearers are hearing with difficulty, and when a musician complains of a want of support, or a sense of something suffocating or stifling in the room, it is equally certain that the richness of his tones cannot be properly heard.

Perhaps echo may under rare circumstances form an exception, and part of the auditory may be annoyed by this defect when the speaker is not; but this will probably be of rare occurrence.

The existence of a defect being once established, the testimony of auditors, or, what is better, a personal visit to every part of the building when in use will enable the architect to satisfy himself in what portions it is perceptible, and this, coupled with his observations on the form of the building and its materials, will ordinarily enable him to satisfy himself as to the probable cause of the evil, and consequently the most suitable remedies to suggest; that is, if any remedy at all is possible, for many bad rooms are almost past cure—their defects can probably be only palliated. In attempts to correct defects in existing buildings, it will be often necessary to act to a great extent experimentally, and the value of a knowledge of acoustics will not be that it will enable the architect to predict with confidence what remedy will infallibly succeed, but rather that it will enable him better to understand what expedient may be tried with the greatest chance of success, and to indicate the exact manner in which any remedy which it is proposed to try should be applied.

In the erection of new buildings a greater approach to certainty seems attainable, not that any laws or principles can be laid down which will render it unnecessary for the architect to proceed with care, judgment, and tact, and to endeavour to accumulate a stock of experience by the study of existing buildings. If, however, certain broad principles exist, such as it has been the aim of this manual to develop and illustrate, and if certain qualities of a building, or circumstances connected with it, are conducive to success, and certain others are ordinarily, perhaps invariably, accompanied by failure, it does not seem extravagant to say that every architect has it in his power, by carefully incorporating with his design those proportions, materials, and arrangements which are proved advantageous, and excluding those which are injurious, to secure beforehand that his building, when erected, shall be favourable and not unfavourable in its influence on sound.

APPENDIX.

BOOKS OF REFERENCE.

I.—BOOKS OF REFERENCE ON THE SCIENCE OF ACOUSTICS.

1. Sir John Herschel. "Sound." The treatise under that heading in the "Encyclopædia Metropolitana," republished separately. London, 1849.

> The best treatise in English, but having been written previous to A. D. 1830, this work does not include the most modern discoveries, many of which are of great interest.

2. Savart. "L'Institut, Journal des Academies, &c." Paris.

> Volumes for 1839 and 1840 contain a "Cours d'Acoustique, par Savart," being lectures delivered in Paris by him, embodying the results of his own researches, as well as those of previous experimenters, and forming a work of the highest order of merit.

3. Biot. "Précis Elémentaire de Physique." Paris.

> A recognised standard authority.

"Mémoires de la Société d'Arcueil," vol. ii. Paris, 1807.

> Contains contributions by M. Biot.

4. Pouillet. "Cours de Physique," 7th edit. Paris, 1856.

> Includes a lucid and comprehensive treatise on the science of sound.

5. Chladni. "Traité d'Acoustique." Paris, 1809.

> A re-issue in French, with additions, of a work previously published by the author in German. A standard work. By the same author there are also two smaller works, "Entdeckungen," 1787, and "Neue Beiträge zur Akustik," 1817. "Allgemeine Musikalische Zeitung," from A. D. 1821 to A. D. 1827 inclusive, also contains valuable papers on matters connected with acoustics, contributed by Chladni.

6. Sir John Leslie. The article "Acoustics," contributed to the "Encyclopædia Britannica."

> In the 7th edition of the "Encyclopædia," supplementary matter, of which there was need, is added by another writer.

7. Mary Somerville. "Connexion of the Physical Sciences." London.

8. Wheatstone. Papers contributed to the "Quarterly Journal of Science, Literature, and Art." London, 1827—9.

"Journal of Royal Institution." London, 1830—31.

"Proceedings of Royal Institution."

"Reports of British Association."

The most valuable contributions which England has furnished to the science of acoustics lie scattered among these papers.

9. "Annales de Chimie," &c., from A. D. 1816.

Contains many valuable contributions by Savart, Wertheim, Lissajoux, and others.

10. Hassenfratz. "Journal de Physique et de Chimie," vol. lix. Paris.

Contains, at p. 18, an abstract of Hassenfratz's admirable paper on the speaking-trumpet.

11. Arnott's "Elements of Physics."

12. Brewer on "Sound." London, 1854.

13. Weber. "Wellenlehre." Leipzig, 1825.

A treatise on the doctrine of waves of light, sound, and ponderable fluids.

14. Scott Russell. "Report on Waves," made to meetings of British Association in 1842—43, and printed in their Reports for 1844.

Various Encyclopædias and treatises on physics might have been also named, as giving more or less complete accounts of the science.

In some of the above-mentioned works, especially those of Sir John Herschel and Chladni, copious references are given to the various writers with whose investigations of the abstruse refinements of acoustics the mathematical student may wish to make himself acquainted, and to the works of earlier writers.

II.—BOOKS OF REFERENCE ON ACOUSTICS AS APPLIED TO BUILDINGS.

1. Lachéz. "Acoustique et Optique des Salles de Réunions Publiques," Par Théodore Lachéz, Architecte. Paris, 1848.

Reference has been repeatedly made to this little work, a treatise of real value to the architect.

2. RHODE. "Théorie der Verbreitung des Schalles für Baukünstler," (*The Theory of the Propagation of Sound for Architects,*) J. G. Rhode. Berlin, 1800.

> This tract, devoted mainly to theatres, does not exceed the dimensions of a short pamphlet, and is recommended by Chladni as preferred by him to any others he had seen.

3. CHLADNI. "Traité d'Acoustique," "Allgemeine Musikalische Zeitung," for 30th August, 1826.

> These publications have been already named in the first list. In the "Traité," by Chladni, several sections are devoted to the arrangement of buildings for sound; and in the number of the "Zeitung" indicated, there is a good paper contributed by him, on the same subject. In both cases he coincides pretty closely with Rhode's views, but adds to them.

4. OTTMER. "Architectonische mittheilungen." 1830.

> Gives an account of the construction of the Theatre at Berlin.

5. SAUNDERS. "On Theatres."

> "A Treatise on Theatres," by George Saunders. London, 1790. Not very profound, nor everywhere correct, but of value.

6 WYATT. "Observations on the Principles of a Design for a Theatre." London, 1811.

> Quoted largely by Gwilt, in his "Encyclopædia."

7. INMAN. "On Ventilation, Warming, and Sound." London, 1836.

> An abstract of the "Evidence taken before a Select Committee (of the House) to consider the best modes of ventilating and warming the New Houses of Parliament." The evidence of Professor Faraday and Dr. Reid is given pretty fully in this abstract. The original Report is dated 2nd Sept., 1835.

8. WEBSTER. "On the Principles of Sound, and their Application to the New Houses of Parliament." 1840.

9. DR. REID. "On Warming and Ventilation."

> Includes some remarks on acoustic arrangement of buildings; in substance similar to his evidence, for which see Inman (7).

10. MATTHEWS. "Observations on Sound."

11. SCOTT RUSSELL. Two papers read before the Royal Institution of British Architects, in February, 1847.

> These were very valuable. An abridged report is to be found in the "Builder," for 1847, pages 82 and 118, and the "Building News" for Nov. 26, Dec. 3, and Dec. 10, 1858.

12. Blackburn. "Description of a Parabolic Sounding-board, erected in Attercliff Church," by the Rev. John Blackburn, M.A. Pamphlet.) London, 1829.

13. A Paper read by the Author of this volume before the Architectural Association, and printed in the "Building News" for Nov. 19, 1858.

A Paper read by the same before the Royal Institute of British Architects, December, 1860, printed in their "Transactions" and in the Architectural Journals.

ON BELLS.

14. Chladni. "Neue Beiträge zur Akustik." 1817.

15. Denison. "On Clocks and Watches, and Bells," forming volume No. 67, 68 of this series.

16. "Philosophical Transactions," vol. xlviii. page 195.

17. "Copy of Report on Condition of the Great Bell of the New Palace of Westminster," ordered by the House of Commons to be printed, August, 1860.

Contains reports by Professor Tyndall, Professor Airey, and Dr. Percy.

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THE END.

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